MECHANICAL PROPERTIES OF AL-AL\textsubscript{2}O\textsubscript{3} COMPOSITES

Part I : SAP-ISML

by

D.J. BOERMAN, M. GRIN and M. VEAUX

1969

Joint Nuclear Research Center
Ispra Establishment - Italy

Metallurgy and Ceramics
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Most of the results, described in this report, were realised between 1960 and 1967 in three research centers: JRC-Ispra, ISML, Novara, and Battelle Institut, Frankfurt.

The first chapter describes in short the fabrication process of the semi-finished products (bars and tubes) and finished products (canning tubes and pressure tubes).
The second chapter deals with the mechanical properties of the SAP-alloys in general. Essentially the chapter consists of:
— talks with results of tension-, compression-, creep- and fatigue tests at various temperatures;
— diagram with the mechanical properties as a function of temperature or percentage of aluminium oxide.

The third chapter describes the experimental conditions and some physical properties of SAP.
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KEYWORDS

MECHANICAL PROPERTIES
SAP
FABRICATION
TESTING
TEMPERATURE
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INTRODUCTION
Under the Orgel Program, Euratom envisaged the possibility of using aluminium alumina composites (Sintered Aluminium Product) for cladding fuel elements (temperature 450°C) and for pressure tubes (temperature 450°C and pressure 20 atm.).

The most important work done on such products with the aim of making them suitable for use in the nuclear field was carried out either under contracts, specially with the ISML (Istituto Sperimentale dei Metalli Leggeri, NOVARA, Italy), and in the laboratories of Euratom's Joint Research Center at Ispra, Italy, especially in the Metallurgy and Ceramics Division.

The research program at ISML was sponsored by Mr. D. GUALANDI (ISML) and Mr. P. JEHENSON (Euratom) (Ref. 1 to 23).

1. MANUFACTURING PROCESS
1.1 Improvement of the Starting Powders (Ref. 22)

The SAP powders used were commercial products which were manufactured by AIAG up to 1962, after which they were further developed by the West German firm of Eckart-Werke.

1.1.1 SAP Powders Produced by AIAG

The SAP powders of the following grades

<table>
<thead>
<tr>
<th>Grade</th>
<th>Al₂O₃ Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP 960</td>
<td>about 4 wt.% Al₂O₃</td>
</tr>
<tr>
<td>SAP 930</td>
<td>&quot; 7  &quot;</td>
</tr>
<tr>
<td>SAP 895</td>
<td>&quot;10-11&quot;</td>
</tr>
<tr>
<td>SAP 865</td>
<td>&quot;13-14&quot;</td>
</tr>
</tbody>
</table>

were obtained from 99.5% pure aluminium powders which had undergone fairly lengthy milling at room temperature in a dry oxidizing atmosphere in the presence of stearic acid (Refs. 46-59). Work carried out on several tons of these powders showed that the aluminium oxide content of a specific grade

* Aluminium-Industrie AG (Alusuisse)
may differ between extreme limits of \( \pm 1 \) wt.% of \( \text{Al}_2\text{O}_3 \) from the theoretical percentage for the grade.

The results of two analyses carried out on two batches are given below (wt.%):

<table>
<thead>
<tr>
<th>Material</th>
<th>% Al(_2)O(_3)</th>
<th>% Fe</th>
<th>% Si</th>
<th>% Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP 930</td>
<td>7.50</td>
<td>0.27</td>
<td>0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>SAP 895</td>
<td>10.40</td>
<td>0.27</td>
<td>0.11</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The grain size is generally between 50 and 150 microns. The grains have irregular round shapes and are of spongy aspect (Illustration 1).

The work carried out in 1960-62 on these AIAG commercial powders indicated that it was necessary to obtain better defined powders, especially with regard to the homogeneity of the product (\% Al\(_2\)O\(_3\)) and the uniformity of dispersion of the Al\(_2\)O\(_3\) particles in the aluminium matrix.

### 1.1.2 SAP Powders Produced by Eckart-Werke

The powders were developed by the West German firm in accordance with the basic manufacturing procedures established by AIAG. They are heavy powders the oxide content of which is mainly due to natural oxidation during the milling of the aluminium powder at room temperature. The original aluminium is nuclear aluminium of the order of 99.85% purity.

The aluminium oxide content must be as follows:

- SAP 930  \( 6.5 - 7.5 \) wt.% Al\(_2\)O\(_3\)
- SAP 895  \( 10 - 11 \) wt.% Al\(_2\)O\(_3\)

The results of two analyses carried out on two batches are given below (wt.%):
### Material Composition

<table>
<thead>
<tr>
<th>Material</th>
<th>% Al₂O₃</th>
<th>% Fe</th>
<th>% Si</th>
<th>% Zn</th>
<th>% C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP 930</td>
<td>7.25</td>
<td>0.07</td>
<td>0.05</td>
<td>0.01</td>
<td>0.20</td>
</tr>
<tr>
<td>SAP 895</td>
<td>10.35</td>
<td>0.08</td>
<td>0.06</td>
<td>0.01</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### 1.2 Cold-compression and Vacuum Treatment

Commercial products exposed to high temperatures (500-600°C) for several hours showed surface blisters and internal micro-cracks, and consequently insufficient structural stability for nuclear uses (Ref. 36). This serious drawback was due to the high residual gas content (mainly hydrogen) of the finished products. While the lowering of the hydrogen content is of fundamental importance, a study has been in progress since 1960 aimed at eliminating this gas by vacuum treatment. The treatment selected, described in patent No. 13.532, registered in Italy on 30 May 1961, has the following main features:

- cold-compression of the powders at about 20 kg/mm² before heating in the vacuum furnace;
- treatment in the 590-620°C range for a period of 20-24 hr;
- vacuum between $10^{-4}$ and $10^{-5}$ mm Hg.

The extruded products contain only a small amount of residual gas, the quantity of which seems to be a function of the oxide content.

### Gas Content

<table>
<thead>
<tr>
<th>Material</th>
<th>Gas content ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP ISML 4% Al₂O₃</td>
<td>1-3</td>
</tr>
<tr>
<td>SAP ISML 7% &quot;</td>
<td>2-5</td>
</tr>
<tr>
<td>SAP ISML 10% &quot;</td>
<td>3-6</td>
</tr>
<tr>
<td>SAP ISML 14% &quot;</td>
<td>4-8</td>
</tr>
</tbody>
</table>
Illustration 1  Structural aspect of Al-$\text{Al}_2\text{O}_3$
powders grade 960
Etching HF 0.5%
Magnification 500 x
Density 1.13 g/cm³
Pressure 20 Kg/mm²
Time: 60 mn

Density 2.2 g/cm³
Temperature between 590-620°C
Time: 20-24 h
Vacuum: 10⁻⁴ - 10⁻⁵ mm Hg

Pressure: 50 Kg/mm²
Time: 1 mn

Density about 2.7 g/cm³
Temperature between 540-590°C

MANUFACTURING PROCESS FOR THE PRODUCTION OF FINISHED PRODUCTS (ref. 23)

Illustration 2
DRAWING OR ROLLING
Illustration 3

Longitudinal microstructure of bars of SAP ISML 7%
Magnification 500 x 2
Etching HF 0.5%
1.3 Hot-compression and Extrusion (Ref. 23, Ill. 2)

1.3.1 Hot-compression

After the vacuum treatment the billet, wrapped in an aluminium foil, is immediately inserted in the container of the press and subjected to a specific pressure of 50 kg/mm² for 30 min.

The process is carried out with a 250 t press for billets 80 mm in diameter and with one of 500 t for billets 110 mm in diameter. At the end of the process, the density of the product is of the order of 2.7 g/cm². The crust is then removed and the billet pickled.

1.3.2 Extrusion

The compacted billets (diameter 110 or 80 mm) are preheated at a temperature of between 540 and 590°C for 3 hr. The temperature of the extrusion container is about 330°C. The process is carried out on one of the three presses, the characteristics of which are given below:

<table>
<thead>
<tr>
<th>Max. force tons</th>
<th>Diameter of starting billet (mm)</th>
<th>Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>80</td>
<td>smooth tubes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rods</td>
</tr>
<tr>
<td>500</td>
<td>80</td>
<td>finned tubes</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>rods</td>
</tr>
<tr>
<td>2700</td>
<td>250</td>
<td>pressure tube</td>
</tr>
</tbody>
</table>

The extrusion velocity varies between 8 m/sec (pressure tube) and 16 to 20 m/sec (rods and finned tubes). In order to obtain rods and tubes, a double extrusion is usually carried out.

The extruded product constitutes the starting material for the rolling and cold drawing processes, which followed in some cases by heat treatment, lead to the finished products.
Illustration 4  Electron micrograph of a bar of SAP-ISML 7% $\text{Al}_2\text{O}_3$

Electron microscope magnification x 8,000
Total magnification x 20,000
1.3.3 Structure of the Extruded Product

The extruded product seems to have a very fine dispersion of Al₂O₃ particles inside the aluminium matrix. The dimension of the particles is between 0.02 and 0.1 micron and the inter-particle distance is of the order of 0.1 to 0.2 micron (see Illustrations 3 and 4).

1.3.4 Definition of the Extrusion Ratio

Any time extruded products (rods, thick-walled tubes, finned tubes) are handled, the strictest definition we can give is the following:

\[
E' = \frac{A_1}{A_2}
\]

\(A_1\): section of the container

\(A_2\): section of the die

However, in current practice another relation which gives quite reliable results is used:

\[
E = \frac{S_1}{S_2}
\]

\(S_1\): section of the container

\(S_2\): section of the extruded product

It is the latter relation which will be taken into consideration in our study.

1.3.5 Influence of the Extrusion Ratio on the Mechanical Properties

It is interesting to note that the value \(E\) is not sufficient to characterize the state of deformation of the material. For example, a finned tube or a round rod extruded at the same extrusion ratio will not give an equivalent strain hardening and consequently the mechanical properties will not be comparable. For instance, the final extrusion ratio for rods Ø 9.5 and for finned tubes are approximately the same (comprised between 70 and 80). However, the longitudinal strength of finned tubes is 18% higher (see Section 3.4.2 and Histograms Fig. 117).

In order to examine this influence in the simple case of rods, we performed tensile tests at 20 and 450°C on rods of SAP ISML 7% and 10% of various extrusion ratios respectively prepared from the same batch of powder. The characteristics of the material are listed in the table below:
<table>
<thead>
<tr>
<th>%Al₂O₃</th>
<th>Bar Ø (mm)</th>
<th>Extrusion ratio</th>
<th>Batch No. (extrusion)</th>
<th>Batch No. (powder)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7%</td>
<td>9.5</td>
<td>76</td>
<td>3,504/3</td>
<td>M 133</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>27</td>
<td>3,448/1</td>
<td>M 129</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>14</td>
<td>3,447/1&amp;2</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>13</td>
<td>3,504/1&amp;2</td>
<td>M 133</td>
</tr>
<tr>
<td>10%</td>
<td>9.5</td>
<td>76</td>
<td>3,240/1</td>
<td>M 4041</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>27</td>
<td>3,239-3,240/2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>14</td>
<td>3,237-3,238</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>13</td>
<td>3,234-3,235-3,236</td>
<td></td>
</tr>
</tbody>
</table>

For the 9.5 mm Ø bar, the test specimen was as represented on Fig. 3, but for the others, the cross section was greater in order to maintain constant the ratio

\[
R = \frac{\text{specimen cross section}}{\text{bar cross section}} = 0.18
\]

However, for all specimens, the ratio \( \frac{\text{length}}{\text{diameter}} = 7.5 \) was maintained constant (see Section 3.1.1.1.1 and Fig. 1.2.3).

The results obtained show that the extrusion ratio influences only the values of elongation at breaking point (eₚb).

1.4 Drawing (Ref. 23)

This procedure has mainly been used for the fabrication of smooth tubes and pressure tubes. The deformation ratio as a percentage, obtained either by drawing or by rolling without intermediate annealing, is given by the following relation:

\[
H = \frac{S - s}{s} \times 100
\]

\( H \) : ratio of cold-deformation in %

\( S \) : initial section of the material

\( s \) : final section of the material

1.5 Rolling (Ref. 23)

The starting material consists of plates of 50 x 12 mm or 30 x 2.5 mm. These are either directly cold-rolled or partly hot-rolled (40 < H < 70%) and then finished at room temperature.
1.5.1 Hot-rolling

The extruded rough shapes are first preheated to 530°C for 24 hr and then rolled transverse to the extrusion direction until a deformation ratio of 50% is obtained, and then parallel to the extrusion direction until a ratio of 70% is reached.

1.5.2 Cold-rolling

This is carried out either directly on the extruded material or on materials that have already undergone hot-rolling deformation. The table below gives the deformation ratios obtained by the two methods:

<table>
<thead>
<tr>
<th>%Al₂O₃</th>
<th>hot-rolling</th>
<th>extrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>73</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>37</td>
<td>32</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>

Before cold-rolling, an annealing treatment of 2 hr at 530°C is necessary. In the case of SAP ISML 4 and 7% deformation ratios of 99% are obtained.

1.6 Fabrication of Rods (Ref. 23)

Up to the end of 1965 (batch No. 2500) the starting billet (hot-compacted) had a diameter of 78.5 mm. The results of the mechanical tests on rods presented in this document concern only the extruded materials made from billets 78.5 mm in diameter.

Characteristics of the first extrusion

diameter of container: 80 mm
dimension of starting billet: 78.5 x 140 mm
diameter of billet obtained: 58 mm
extrusion ratio: E = 1.9
extrusion rate: 1.3 m/min
temperature: 568°C
Afterwards the second extrusion is carried out directly on the final diameter of the rod with the same temperature conditions. The extrusion ratios relating to the various diameters of rods extruded from compacts of O.D. 80 mm are given in the following table.

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>1st Extrusion</th>
<th>2nd Extrusion</th>
<th>Final Extrusion ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Extrusion</td>
<td>Extrusion</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>1.9</td>
<td>23</td>
<td>6.8</td>
</tr>
<tr>
<td>21</td>
<td>8.2</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>14</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>9.5</td>
<td>40</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

1.7 Fabrication of Cladding Tubes (Ref. 23)

The smooth tubes are fabricated by extrusion followed by cold-drawing, the finned tubes by extrusion only.

1.7.1 Smooth Tubes

Since the mechanical tests were only carried out on tubes 13.1 x 14.7 mm in diameter we can limit ourselves to indicating the fabrication conditions of smooth tubes of these dimensions only.

1.7.1.1 Extrusion

The starting material is a cylindrical hollow billet through which a lubricated, slightly conical mandrel is passed which is of the same diameter as the internal diameter of the tube after extrusion (extrusion by free floating mandrel).

In the case considered here, the extruded tube has diameters of 16 and 14 mm (E = 59). The extrusion temperature is 571°C and the velocity is between 16 and 20 m/min.
1.7.1.2 Cold-drawing

The cold-drawing characteristics for the tubes concerned are given below:

<table>
<thead>
<tr>
<th></th>
<th>Diameter of Die (mm)</th>
<th>Diameter of Mandrel (mm)</th>
<th>Wall Thickness of Tube (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st step</td>
<td>15.0</td>
<td>13.4</td>
<td>0.8</td>
</tr>
<tr>
<td>2nd step</td>
<td>14.7</td>
<td>13.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Ratio of final cold-deformation: \( H = 25\% \)

cold-drawing rate: 12 m/min

1.7.2 Finned tubes (Ref. 23)

The extrusion is carried out in two steps on a 500 t press at a temperature of 575°C starting from a hot-compacted billet 110 mm in diameter. The first extrusion gives a billet either 80 mm in (\( E = 2 \)) diameter of 60 mm (\( E = 4 \)). The extrusion rate is 1.3 m/min. Afterwards a central hole with a diameter equal to the final internal diameter of the hole is drilled. A second extrusion at rates between 16 and 20 m/min results in the desired profile. The extrusion ratios are between 17 and 20. The method is the same as that applied for extruding smooth tubes (free floating mandrel). The fins may be straight or helicoidal.

1.8 Fabrication of Pressure Tubes

These are tubes of large diameter (about 100 mm). As in the case of smooth tubes, they are first extruded and then cold-drawn.

1.8.1 Extrusion

The process is carried out at a temperature of 570°C on a 2700 t press followed by annealing for 2 hr at 540°C. The extrusion rate is of the order of 8 m/min. The dimensional characteristics are listed in the table below:
dimension of the extruded tube

<table>
<thead>
<tr>
<th></th>
<th>before extrusion</th>
<th>after extrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ID mm OD mm</td>
<td>ID mm OD mm</td>
</tr>
<tr>
<td>1st extrusion</td>
<td>98 250</td>
<td>97 198</td>
</tr>
<tr>
<td>2nd extrusion</td>
<td>97 198</td>
<td>96 102</td>
</tr>
</tbody>
</table>

At the end of the process the extruded tube is annealed for 2 hr at 540°C.

1.8.2 Cold-drawing

The cold-drawing is carried out in two steps; after each step annealing for 2 hr at 540°C is necessary. The dimensional characteristics are given below:

dimension of the drawn tube

<table>
<thead>
<tr>
<th></th>
<th>before cold-drawing</th>
<th>after cold-drawing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ID mm OD mm</td>
<td>ID mm OD mm</td>
</tr>
<tr>
<td>1st step</td>
<td>96 102</td>
<td>94.05 100.4</td>
</tr>
<tr>
<td>2nd step</td>
<td>94.05 100.4</td>
<td>92.2 98.4</td>
</tr>
</tbody>
</table>

2. STUDY OF THE MATERIAL

2.1 Research Laboratories

Euratom has undertaken studies on the improvement of this material in the laboratories of the Ispra Joint Research Center and has concluded contracts with several companies.

With the Italian firm of Montecatini, it has drawn up two contracts: a research contract to be carried out in the laboratories of the Istituto Sperimentale dei Metalli Leggeri (ISML), Novara, and a contract for the production of bars, cladding tubes and pressure tubes on a semi-industrial scale.

A research contract concerning creep tests has also been concluded with the Battelle Institute, Frankfurt, Germany.
Some other results, reported here, were obtained by the Danish Atomic Energy Commission at its Risø research establishment. Other tests were conducted by the Civilian Atomic Power Department of the Canadian General Electric Company Ltd. (Peterborough, Ontario) and reprinted in the AECL publications (Atomic Energy of Canada Ltd., Chalk River, Ontario).

2.2 Presentation of Results

The main results will be presented in the form of diagrams whenever possible; the experimental conditions, the comments and some complementary results in tabular form will be found with all the references in an appendix at the end of the report.

2.2.1 Denomination of Material

The material is characterized by its percentage number (4, 7, 10 or 14% principally). This refers to the nominal percentage of $\text{Al}_2\text{O}_3$ by weight in the aluminium matrix. Often the real weight percentage differs by at least ±1 wt.% of $\text{Al}_2\text{O}_3$. The results refer only to SAP produced in standard conditions (see Section 1). In addition, all the results concern SAP manufactured by ISML, which is named SAP ISML in order to distinguish it from, for example:

- SAP AIAG
- FRITTOZAL (TLH)
- APM alloys, etc.

The material is also given a batch number at the beginning of the fabrication process. The batch numbers are allocated chronologically, so this number indicates the fabrication period. The principal fabrication characteristics for a given batch number are collected in tables published in the quarterly progress reports of ISML, Novara.

Table 1 gives a list of the batch numbers for the specific quarterly progress reports and for the various types of powders used.
Table 1

Fabrication Data of the Various Batches of SAP

<table>
<thead>
<tr>
<th>No. of Batch</th>
<th>Date of fabrication</th>
<th>Ref.</th>
<th>Type of powder employed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 - 5 - 1960</td>
<td>...1</td>
<td>4% 7% 10% 14%</td>
</tr>
<tr>
<td>82</td>
<td>30 - 7 - 1960</td>
<td>...2</td>
<td></td>
</tr>
<tr>
<td>128</td>
<td>31 - 10 - 1960</td>
<td>...3</td>
<td></td>
</tr>
<tr>
<td>173</td>
<td>15 - 2 - 1961</td>
<td>...4</td>
<td></td>
</tr>
<tr>
<td>251</td>
<td>15 - 5 - 1961</td>
<td>...5</td>
<td></td>
</tr>
<tr>
<td>347</td>
<td>31 - 7 - 1961</td>
<td>...6</td>
<td></td>
</tr>
<tr>
<td>441</td>
<td>30 - 11 - 1961</td>
<td>...7</td>
<td></td>
</tr>
<tr>
<td>555</td>
<td>28 - 2 - 1962</td>
<td>...8</td>
<td></td>
</tr>
<tr>
<td>734</td>
<td>31 - 5 - 1962</td>
<td>...9</td>
<td></td>
</tr>
<tr>
<td>851</td>
<td>30 - 9 - 1962</td>
<td>...10</td>
<td></td>
</tr>
<tr>
<td>926</td>
<td>31 - 12 - 1962</td>
<td>...11</td>
<td></td>
</tr>
<tr>
<td>1137</td>
<td>30 - 4 - 1963</td>
<td>...12</td>
<td></td>
</tr>
<tr>
<td>1241</td>
<td>31 - 8 - 1963</td>
<td>...13</td>
<td></td>
</tr>
<tr>
<td>1344</td>
<td>31 - 12 - 1963</td>
<td>...14</td>
<td></td>
</tr>
<tr>
<td>1636</td>
<td>30 - 6 - 1964</td>
<td>...15</td>
<td></td>
</tr>
<tr>
<td>1831</td>
<td>31 - 10 - 1964</td>
<td>...16</td>
<td></td>
</tr>
<tr>
<td>1939</td>
<td>31 - 12 - 1964</td>
<td>...17</td>
<td></td>
</tr>
<tr>
<td>2209</td>
<td>30 - 4 - 1965</td>
<td>...18</td>
<td></td>
</tr>
<tr>
<td>2353</td>
<td>31 - 8 - 1965</td>
<td>...19</td>
<td></td>
</tr>
<tr>
<td>2483</td>
<td>31 - 12 - 1965</td>
<td>...20</td>
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<td>2680</td>
<td>30 - 4 - 1966</td>
<td>...21</td>
<td></td>
</tr>
<tr>
<td>3172</td>
<td>31 - 8 - 1966</td>
<td>...21A</td>
<td></td>
</tr>
<tr>
<td>3440</td>
<td>31 - 12 - 1966</td>
<td>...21B</td>
<td></td>
</tr>
<tr>
<td>3740</td>
<td>30 - 4 - 1967</td>
<td>...21C</td>
<td></td>
</tr>
<tr>
<td>3827</td>
<td>31 - 8 - 1967</td>
<td>...21C</td>
<td></td>
</tr>
</tbody>
</table>

Ref. = Eckart-Werke and AIAG

Type of powder employed:
- 4%, 7%, 10%, 14%
2.2.2 Presentation of Diagrams

Normally metric units were used, but whenever the references employed British units, both are reported. As far as possible standard scales were adopted for the different graphs in order to facilitate comparison. The dimensions of specimens often influence the results, so they were given. For every cumulative diagram, reference is made to the figure numbers in the original individual diagrams and their respective document reference numbers.

The general scheme of presentation of the results will be the following:

- a table and a figure (Table 2 and Illustration 5) show all the symbols and terms used in English, French and German to characterize the mechanical properties in tensile and compression testing.

- seven tables summarize the main mechanical properties of the four grades of SAP for bars, smooth tubes and finned tubes (Tables 3 to 9).

- an index of all the measured mechanical and physical properties of SAP with reference to the corresponding figures (Tables 10 and 11).

- the figures gathered according to the type of test:

Semi-finished products
  • Mechanical properties
    Tensile tests
    Compression tests
    Creep tests
    Relaxation tests
    Impact strength tests
    Hardness tests
    Fatigue tests
    Evolution of rod production
  • Physical properties

Finished products
  Various mechanical tests like tensile tests, compression tests, burst tests and fatigue burst tests.
SYMBOLS
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
<th>English</th>
<th>French</th>
<th>German</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{pr}$</td>
<td>Proportional elastic load</td>
<td>kg</td>
<td></td>
<td>charge à la limite de proportionnalité</td>
<td>Kraft an der Proportionalitätsgrenze</td>
</tr>
<tr>
<td>$P_{0.2}$</td>
<td>0.2 offset yield load</td>
<td>kg</td>
<td></td>
<td>charge à la limite élastique à 0,2%</td>
<td>Kraft an der 0,2 Streckgrenze</td>
</tr>
<tr>
<td>$P_u$</td>
<td>upper load</td>
<td>kg</td>
<td></td>
<td>charge maximum</td>
<td>Maximum-Kraft</td>
</tr>
<tr>
<td>$A_0$</td>
<td>original gauge cross-section</td>
<td>mm$^2$</td>
<td></td>
<td>section originale</td>
<td>originaler Querschnitt</td>
</tr>
<tr>
<td>$L_{pu}$</td>
<td>plastic uniform elongation</td>
<td>mm</td>
<td></td>
<td>allongement plastique réparti</td>
<td>plastische Gleichmassverlängerung</td>
</tr>
<tr>
<td>$L_{pb}$</td>
<td>plastic elongation at breaking point</td>
<td>mm</td>
<td></td>
<td>allongement plastique à la rupture</td>
<td>plastische Verlängerung beim Bruch</td>
</tr>
<tr>
<td>$L_0$</td>
<td>original gauge length</td>
<td>mm</td>
<td></td>
<td>base de mesure</td>
<td>originale Messlänge</td>
</tr>
<tr>
<td>$S_{pr}$</td>
<td>engineering proportional elastic limit</td>
<td>kg/mm$^2$</td>
<td></td>
<td>contrainte à la limite de proportionnalité</td>
<td>technologische Proportionalitätsgrenze</td>
</tr>
<tr>
<td>$S_{0.2}$</td>
<td>engineering 0.2 offset yield stress</td>
<td>kg/mm$^2$</td>
<td></td>
<td>limite élastique à 0,2%</td>
<td>technologische 0,2 Streckgrenze</td>
</tr>
<tr>
<td>$S_u$</td>
<td>engineering maximum tensile stress</td>
<td>kg/mm$^2$</td>
<td></td>
<td>contrainte maximum</td>
<td>technologische Zugfestigkeit</td>
</tr>
<tr>
<td>$e_{pu}$</td>
<td>engineering plastic uniform strain</td>
<td>%</td>
<td></td>
<td>allongement plastique (unitaire) réparti</td>
<td>technologische plastische Gleichmassdehnung</td>
</tr>
<tr>
<td>$e_{pb}$</td>
<td>engineering plastic strain at breaking point</td>
<td>%</td>
<td></td>
<td>allongement plastique unitaire à la rupture</td>
<td>technologische plastische Bruchdehnung</td>
</tr>
<tr>
<td>$E$</td>
<td>Young's Modulus of elasticity</td>
<td>kg/mm$^2$</td>
<td></td>
<td>module élastique (module d'Young)</td>
<td>Elastizitätsmodul</td>
</tr>
</tbody>
</table>
ILLUSTRATION 5

GENERAL FORM
OF TENSION AND COMPRESSION CURVES
AND SYMBOLS EMPLOYED

Tension specimen \( \phi = 4 \text{mm} \)
\( l_0 = 30 \text{mm} \)
(fig. 3)

Compression specimen \( \phi = 4 \text{mm} \)
\( l_0 = 4 \text{mm} \)

Stress \( S (\text{Kg/mm}^2) \)

% strain

\( \varepsilon_{pu} \)
\( \varepsilon_{pb} \)

\( A, A' \)
\( B, B' \)
\( C, C' \)
\( S_u \)
\( S_{Q2} \)
SUMMARY OF THE MAIN MECHANICAL PROPERTIES
## MAIN MECHANICAL PROPERTIES

<table>
<thead>
<tr>
<th>Type of Material</th>
<th>Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>bars SAP 4%</td>
<td>3</td>
</tr>
<tr>
<td>bars SAP 7%</td>
<td>4</td>
</tr>
<tr>
<td>bars SAP 10%</td>
<td>5</td>
</tr>
<tr>
<td>bars SAP 14%</td>
<td>6</td>
</tr>
<tr>
<td>smooth tubes SAP 4%</td>
<td>7</td>
</tr>
<tr>
<td>smooth tubes SAP 7%</td>
<td>8</td>
</tr>
<tr>
<td>finned tubes SAP 7%</td>
<td>9</td>
</tr>
</tbody>
</table>
Table 3

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Room temperature properties</th>
<th>High temperature properties</th>
<th>References of Figures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile test (1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_u$ (kg/mm$^2$)</td>
<td>$S_{0.2}$ (kg/mm$^2$)</td>
<td>$e_{pu}$ (%)</td>
</tr>
<tr>
<td>Tensile</td>
<td>20.0</td>
<td>13.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Tensile</td>
<td>24.5</td>
<td>18</td>
<td>12.2</td>
</tr>
<tr>
<td>Compression</td>
<td>34.8</td>
<td>21.2</td>
<td>16.0</td>
</tr>
<tr>
<td>Compression</td>
<td>32.8</td>
<td>19.6</td>
<td>15.3</td>
</tr>
<tr>
<td>Creep tests</td>
<td></td>
<td></td>
<td>Max. stress</td>
</tr>
<tr>
<td>(Maximum admissible stress for 10,000 hrs life)</td>
<td></td>
<td></td>
<td>(kg/mm$^2$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>426</td>
</tr>
<tr>
<td>Fatigue limit in rotating bending</td>
<td>$8.5$</td>
<td></td>
<td>Maximum stress</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$400$</td>
</tr>
<tr>
<td>Young's Modulus</td>
<td></td>
<td></td>
<td>$7,200$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$400$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$450$</td>
</tr>
</tbody>
</table>

(1) 6 to 15 specimens for each temperature
### Main Mechanical Properties of SAP ISML 7%

**Table 4**

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Room temperature properties</th>
<th>High temperature properties</th>
<th>References of Figures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile tests(1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Creep tests</td>
<td>Maximum admissible stress for 10,000 hrs. life.</td>
<td>Max. stress (kg/mm²)</td>
<td>Elongation at rupture (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue limit in rotating bending</td>
<td>Maximum stress (kg/mm²)</td>
<td>Maximum stress (kg/mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) 5 to 10 specimens for each temperature
### Table 5

<table>
<thead>
<tr>
<th>Type of Test</th>
<th>Room Temperature Properties</th>
<th>High Temperature Properties</th>
<th>References of Figures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( S_u (\text{kg/mm}^2) )</td>
<td>( S_{0.2} (\text{kg/mm}^2) )</td>
<td>( e_{pu} (%) )</td>
</tr>
<tr>
<td>Tensile tests (1)</td>
<td>29.8</td>
<td>21.5</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>30.8</td>
<td>24.8</td>
<td>8.2</td>
</tr>
<tr>
<td>Compression tests</td>
<td>47.6</td>
<td>28.6</td>
<td>21.3</td>
</tr>
<tr>
<td>Creep tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Maximum admissible</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stress for 10,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hrs life)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue limit in</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rotating bending</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum stress (</td>
<td>9.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kg/mm²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum stress (</td>
<td></td>
<td>400</td>
<td>5.8</td>
</tr>
<tr>
<td>Young's Modulus (</td>
<td>7,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kg/mm²)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) 6 to 11 specimens for each temperature
### Table 6

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Room temperature properties</th>
<th>High temperature properties</th>
<th>References of Figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile tests (1)</td>
<td></td>
<td></td>
<td>17-18 (Eur)</td>
</tr>
<tr>
<td></td>
<td>$S_u$ (kg/mm²)</td>
<td>$S_{0.2}$ (kg/mm²)</td>
<td>$e_{pu}$ (%)</td>
</tr>
<tr>
<td></td>
<td>36.0</td>
<td>26.0</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>37.7</td>
<td>30.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Compression tests</td>
<td>57.2</td>
<td>47.6</td>
<td>34.7</td>
</tr>
<tr>
<td>Creep tests (Maximum admissible stress for 10,000 hrs. life).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue limit in rotating bending</td>
<td>Maximum stress (kg/mm²)</td>
<td>Maximum stress (kg/mm²)</td>
<td></td>
</tr>
<tr>
<td>Young's Modulus (kg/mm²)</td>
<td>7,700</td>
<td>400</td>
<td>5,300 ± 50</td>
</tr>
</tbody>
</table>

(1) 4 to 6 specimens for each temperature.
### Table 7

**Main Mechanical Properties of Smooth Tubes in SAP ISML 4%**

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Mechanical and thermal treatment</th>
<th>Room temperature properties</th>
<th>High temperature properties</th>
<th>Reference figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile test</td>
<td>Extruded then annealed</td>
<td>$S_u$ (kg/mm$^2$)</td>
<td>22.5</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Extruded, Cold-drawn, then annealed</td>
<td>$S_{0.2}$ (kg/mm$^2$)</td>
<td>14</td>
<td>22.3</td>
</tr>
<tr>
<td>Creep under internal gas pressure</td>
<td>Annealed</td>
<td>$e_{pb}$ (%)</td>
<td>400</td>
<td>Maximum stress (kg/mm$^2$) for a life of 2,000 hrs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test temperature °C</td>
<td>400</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$S_u$ (kg/mm$^2$)</td>
<td>450</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Table 8

Main mechanical properties of smooth tubes in SAP ISML 7%

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Mechanical and thermal treatment of the material</th>
<th>Room temperature properties</th>
<th>High temperature properties</th>
<th>References of figures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$S_u$ (kg/mm$^2$)</td>
<td>$S_{0.2}$ (kg/mm$^2$)</td>
<td>$\varepsilon_{pb}$ (%)</td>
</tr>
<tr>
<td>Tensile Test</td>
<td>Extruded then annealed</td>
<td>27.3</td>
<td>14.5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Extruded, Cold-drawn then annealed</td>
<td>30</td>
<td>22</td>
<td>5</td>
</tr>
<tr>
<td>Creep under internal gas pressure</td>
<td>Annealed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cold-drawn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cold-drawn then annealed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References

105
106
107
110
111
Main high temperature mechanical properties of finned tubes in SAF ISM 7

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Test temperature °C</th>
<th>Rupture stress (kg/mm²)</th>
<th>Elongation at rupture (%)</th>
<th>References of Sections and Figures</th>
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</thead>
<tbody>
<tr>
<td>Tensile tests</td>
<td>450</td>
<td>6.8 9 10.8</td>
<td>1 3.2 5</td>
<td>Fig. 112</td>
</tr>
<tr>
<td>Compression tests</td>
<td>450</td>
<td>6.9 7 7.4</td>
<td>0.16(1) 0.26(1) 0.39(1)</td>
<td>Sect. 3.3.2</td>
</tr>
<tr>
<td>Burst test (tangential stress)</td>
<td>460</td>
<td>5.1 5.6 6.0</td>
<td></td>
<td>Sect. 3.3.2</td>
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<tr>
<td>Burst test on tubes with internal artificial defects (15% wall thickness)</td>
<td>460</td>
<td>5.0 5.3 5.55</td>
<td></td>
<td>Sect. 3.3.2</td>
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<tr>
<td>Fatigue tests with internal gas pressure (with and without internal defects)</td>
<td>460</td>
<td>4.1(2) 4.3(2) 4.45(2)</td>
<td></td>
<td>Sect. 3.3.2</td>
</tr>
<tr>
<td>Creep tests in compression</td>
<td>460</td>
<td>4.4(3)</td>
<td></td>
<td>Sect. 3.3.2</td>
</tr>
</tbody>
</table>

(1) In this case, the elongation corresponds to \( \varepsilon_{pu} \).
(2) For a life to rupture of 5,000 cycles.
(3) For a life to rupture of about 5,000 hours.
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**Mechanical Properties of Semi-finished Products**

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Figures as a function of temperature for each grade of SAP</th>
<th>Figures as a function of oxide content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SAP 4%</td>
<td>SAP 7%</td>
</tr>
<tr>
<td>Tensile</td>
<td>11-12-29</td>
<td>13-14</td>
</tr>
<tr>
<td></td>
<td>12-20-21-22</td>
<td>22-23-24-25</td>
</tr>
<tr>
<td>Compression</td>
<td>35-36-37</td>
<td>35-36-37</td>
</tr>
<tr>
<td></td>
<td>40-52-55-56</td>
<td>41-42-43-44</td>
</tr>
<tr>
<td></td>
<td>61</td>
<td>51-60-61</td>
</tr>
<tr>
<td>Relaxation</td>
<td>64-65-66</td>
<td>65</td>
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<tr>
<td>Impact</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>Hardness</td>
<td>69a-72-70a-71-73</td>
<td>69a-70a-70b-71-73</td>
</tr>
<tr>
<td>Fatigue</td>
<td>75-82-72</td>
<td>76-83-72</td>
</tr>
<tr>
<td>Evolution of</td>
<td>86-87</td>
<td>88-89-90-91</td>
</tr>
<tr>
<td>rod production</td>
<td></td>
<td></td>
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</tbody>
</table>

**NB:** Underlined numbers refer to cumulative figures.
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Physical properties of semi-finished products

<table>
<thead>
<tr>
<th>Property or Test</th>
<th>Figures as a function of temperature for each grade of SAP</th>
<th>Figures as a function of oxide content</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>SAP 4%</td>
<td>SAP 7%</td>
</tr>
<tr>
<td>Young's Modulus</td>
<td>93</td>
<td>93</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>96-97</td>
<td>96-97</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>92-100-101</td>
<td>92-100-101</td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mechanical properties of finished products

<table>
<thead>
<tr>
<th></th>
<th>105-106-107</th>
<th>105-106-107</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile tests on smooth tubes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Creep tests with internal gas pressure on smooth tubes</td>
<td>108-109-115</td>
<td>110-111-116</td>
</tr>
<tr>
<td>Tensile tests on finned tubes</td>
<td>112-113-114</td>
<td>117</td>
</tr>
</tbody>
</table>

NB: Underlined numbers refer to cumulative figures.
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SEMI-FINISHED PRODUCTS

Tensile Tests

Influence of the gauge length on the engineering plastic elongation at breaking point during tensile test.

Fig. 1 and 2

Influence of the extrusion ratio on the elongation $e_{pb}$

Fig. 3

Euratom tensile specimen (TR1)

Fig. 4

ISML tensile specimen

Fig. 5

Influence of test duration on the mechanical properties

Fig. 6

Influence of the crosshead speed on the mechanical properties

Fig. 7, 8, 9

The elastic limit of SAP ISML at 20° and 400° C obtained through different methods

Fig. 9A, 9B, 9C

Tensile tests on SAP 4% Stress $S = f(T)$

Fig. 10

Tensile tests on SAP 4% Strain $e = f(T)$

Fig. 11

Tensile tests on SAP 7% Stress $S = f(T)$

Fig. 12

Tensile tests on SAP 7% Strain $e = f(T)$

Fig. 13

Tensile tests on SAP 10% Stress $S = f(T)$

Fig. 14

Tensile tests on SAP 10% Strain $e = f(T)$

Fig. 15

Tensile tests on SAP 14% Stress $S = f(T)$

Fig. 16

Tensile tests on SAP 14% Strain $e = f(T)$

Fig. 17

Cumulative Euratom results Stress $S_{u} = f(T)$

Fig. 18

Cumulative ISML results Stress $S_{u} = f(T)$

Fig. 19

Cumulative Euratom results Stress $S_{0.2} = f(T)$

Fig. 20

Cumulative ISML results Stress $S_{0.2} = f(T)$

Fig. 21

Cumulative Euratom results Strain $e_{pu} = f(T)$

Fig. 22

Cumulative ISML results Strain $e_{pu} = f(T)$

Fig. 23

Cumulative Euratom results Strain $e_{pb} = f(T)$

Fig. 24

Cumulative ISML results Strain $e_{pb} = f(T)$

Fig. 25

Cumulative results Stress $S_{u}$ & $S_{0.2} = f(\%Al_{2}O_{3})$

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Cumulative stress-rupture curves of different SAP grades at 400°C (ISML results)

Cumulative stress-rupture curves of different SAP grades at 460°C (Euratom results)

Stress to produce 0.1% creep elongation at 400°C (ISML results)

Creep extension after 1,000 hours at 400°C (ISML results)

Stress-rupture curves of SAP 4% at 460°C after heat treatment

Stress-rupture curves of SAP 7% at 460°C (thermal cycling during the creep tests)

Battelle creep specimen

Stress-rupture curve of SAP 4% at 460°C

Scatter of strain values of SAP 4% at 460°C

Stress-rupture curve of SAP 7% at 460°C

Scatter of strain values of SAP 7% at 460°C

AECL creep specimen

Stress-rupture curves of three grades of SAP at 426°C (AECL results)

Cumulative stress-rupture curves at 460°C obtained by different laboratories on SAP ISML 4% and 7%

Relaxation Tests

ISML relaxation specimen

Euratom relaxation specimen

Relaxation curves of SAP 7% at 20°C

Relaxation curves of SAP 7 and 10% at high temperature

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70a Brinell macrohardness of SAP ISML vs temperature (Buratom results)
70b Brinell macrohardness of SAP ISML vs. temperature (ISML results)
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72 Vickers hardness as a function of annealing temperature for SAP 4%, after different deformations
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77 Fatigue curves for SAP 10% at 20 and 400°C
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81 ISML unnotched fatigue specimen for 20°C
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83 Notch effect for SAP 7% at 20°C
84 Notch effect for SAP 10% at 20°C
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95 Electrical resistivity as a function of percentage of $\text{Al}_2\text{O}_3$ at 20°C
96 Electrical resistivity as a function of temperature for different SAP grades (Euratom results)
97 Electrical resistivity as a function of temperature for different SAP grades (ISML results)
98 Electrical resistivity as a function of percentage of oxide at 100 and 500°C
99 Thermal conductivity as a function of temperature for different grades of SAP
100 Thermal conductivity at 100 and 500°C for different grades of SAP
101 Thermal conductivity as a function of temperature for different SAP grades (ISML results)
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102 Thermal conductivity as a function of % Al\(_2\)O\(_3\) at 500°C

103 Thermal conductivity as a function of % Al\(_2\)O\(_3\) at 100°C

104 Density as a function of % Al\(_2\)O\(_3\) (ISML results)

104A Density as a function of % Al\(_2\)O\(_3\) (AEK Risø results)

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(ISML Results)

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106 The elastic limit S\(_{0.2}\) of smooth tubes as a function of percentage of Al\(_2\)O\(_3\) at 20 and 450°C

107 The plastic breaking strain e\(_{pb}\) of smooth tubes as a function of percentage of Al\(_2\)O\(_3\) at 20 and 450°C

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118 Burst tests on finned tubes of SAP ISML 7% (Tangential stress at breaking point vs. depth of defect).

119 Fatigue burst tests on finned tubes of SAP ISML 7% under internal pulsed gas pressure.
SEMI-FINISHED PRODUCTS

TENSILE TESTS
INFLUENCE OF THE SPECIMEN GAUGE LENGTH ON THE VALUES OF PLASTIC STRAIN (ISML Results on SAP ISML 10%) Ref. 14-22

\[ \varepsilon_{pb} = f(T) \] on cylindrical specimens

<table>
<thead>
<tr>
<th>Name of Specimens</th>
<th>( A_{1,5} )</th>
<th>( A_3 )</th>
<th>( A_5 )</th>
<th>( A_{10} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>1,5</td>
<td>3</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>10</td>
<td>20</td>
<td>35</td>
<td>70</td>
</tr>
</tbody>
</table>

![Fig. 1: Influence of Specimen Gauge Length](image1)

![Fig. 2: Influence of Specimen Gauge Length](image2)
EURATOM TENSILE SPECIMEN TR 1
(gauge length = 7.5 x Diameter)

Fig. 3

ISML TENSILE SPECIMEN
(Gauge length = 11.4 Diameter)
Ref. ISML drawing PDc 13/1

Fig. 4
Influence of the extrusion ratio on the elongation $\varepsilon_{pb}$ (Tensile test)

(Euratom results - Specimen Fig 3)
INFLUENCE OF THE TEST DURATION ON THE MECHANICAL PROPERTIES OF SAP ISML 7% (Euratom and ISML results)

<table>
<thead>
<tr>
<th>Test Temperat. °C</th>
<th>Batch N°</th>
<th>Specimen</th>
<th>Ref.</th>
<th>Conventional signs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euratom test</td>
<td>20</td>
<td>1723</td>
<td>3</td>
<td>S, S0.2, e, e pb</td>
</tr>
<tr>
<td>ISML test</td>
<td>400</td>
<td>40-41</td>
<td>4</td>
<td>S, S0.2, e, e pb</td>
</tr>
</tbody>
</table>

Fig. 6
INFLUENCE OF THE CROSSHEAD SPEED ON THE MECHANICAL PROPERTIES OF SAP ISML 4% (Euratom results Ref: 51)

- $S_u$ Engineering maximum tensile stress
- $S_{0.2}$ " 0.2 offset yield stress

Specimen Fig 3
Batch N. 828 - 829 (bars $\varnothing$ 9.5mm)

![Graph showing the influence of crosshead speed on mechanical properties.](image)
INFLUENCE OF THE CROSSHEAD SPEED ON THE MECHANICAL PROPERTIES OF SAP ISML 4%
(Euratom results Ref. 51)

+ epb: Engineering plastic strain at breaking point
Specimen Fig 3 Batch no. 828-829 (bars Ø 9.5mm)

Mean value of crosshead speed cm/mm

Fig. 8
INFLUENCE OF CROSSHEAD SPEED ON THE MECHANICAL PROPERTIES OF SAP ISML 7% (Euratom results Ref.51)

Ω $S_u$: Engineering maximum tensile stress
□ $S_{0.2}$: Offset yield stress

Specimen Fig 3  Batch N.906-907 (bars Ø 9.5)

![Graph showing the influence of crosshead speed on tensile stress and yield stress.](image-url)
INFLUENCE OF THE CROSSHEAD SPEED ON THE MECHANICAL PROPERTIES OF SAP ISML 7%
(Euratom results, Ref: 57)

+ $e_{pb}$ Engineering plastic strain at breaking point
Specimen Fig 3 Batch N. 861 (bars Ø 9.5 mm)

$e_{pb}$ vs. $\gamma$ graph showing the influence of crosshead speed on the mechanical properties of SAP ISML 7% at various temperatures. The graph includes lines for temperatures of 200°C, 100°C, 25°C, 300°C, 386°C, and 600°C. The standard Euratom value is indicated at 386°C.
INFLUENCE OF THE CROSSHEAD SPEED ON THE MECHANICAL PROPERTIES OF SAP ISML 10% (Euratom results Ref.51)

- $S_u$: Engineering maximum tensile stress
- $S_o.2$: 0.2 offset yield stress

Specimen Fig3  Batch N4051 (bars $\phi$ 9.5mm)
INFLUENCE OF THE CROSSHEAD SPEED ON THE MECHANICAL PROPERTIES OF SAP ISML 10% (Euratom results Ref51)

+ Epb: Engineering plastic strain at breaking point
Specimen Fig.3 Batch N.1051 (bar Ø 9.5mm)
THE ELASTIC LIMIT OF SAP ISML
OBTAINED THROUGH DIFFERENT METHODS
(ISML and EURATOM RESULTS)

<table>
<thead>
<tr>
<th>Batch No</th>
<th>% Al₂O₃</th>
<th>S (Kg/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>291</td>
<td>300</td>
<td>321</td>
</tr>
<tr>
<td>95</td>
<td>95</td>
<td>16</td>
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</table>

**ISML Tests**

<table>
<thead>
<tr>
<th>Euratom Tests</th>
<th>% Al₂O₃</th>
<th>S (Kg/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch No</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>289-291</td>
<td>275</td>
<td>280</td>
</tr>
<tr>
<td>9.5</td>
<td>9.5</td>
<td>9.5</td>
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</tbody>
</table>

**EURATOM RESULTS**

<table>
<thead>
<tr>
<th>% Al₂O₃</th>
<th>S (Kg/mm²)</th>
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</thead>
<tbody>
<tr>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>291</td>
<td>300</td>
</tr>
<tr>
<td>95</td>
<td>95</td>
</tr>
</tbody>
</table>

---

Fig. 10

Euratom Results
Batch No 3552
SAP ISML 7%
TENSILE TESTS ON SAP ISML 4% (Euratom Results) Ref. 45-46

Stress $S = f(T)$

- $S_u$: Engineering maximum tensile stress
- $S_{0.2}$: 0.2 offset yield stress

<table>
<thead>
<tr>
<th>Batch No</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>289/291</td>
<td>(1)</td>
</tr>
<tr>
<td>828</td>
<td>(2)</td>
</tr>
<tr>
<td>1346</td>
<td>Black</td>
</tr>
</tbody>
</table>

Specimen Fig. 3 machined on bars $\phi$ 9.5 mm.
TENSILE TESTS ON SAP ISML 4% (Euratom Results Ref. 45-46)

Strain $\Theta = f(T)$

$\Delta e_{pu}$ Engineering plastic uniform strain

$e_{pb}$ Strain at breaking point

<table>
<thead>
<tr>
<th>Batch No</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>289/291</td>
<td>$\Delta (1)$ +</td>
</tr>
<tr>
<td>828</td>
<td>$\Delta (2)$ +</td>
</tr>
<tr>
<td>1346</td>
<td>Black +</td>
</tr>
</tbody>
</table>
TENSILE TESTS ON SAP 1SML 7 %
(Euratom results) Ref 45-46

Stress $S = f(T)$

Determinations:
- $S_{ue}$: Engineering maximum tensile stress
- $S_{0.2}$: Engineering 0.2% offset yield stress

Graph:
- Batch No: 275
- Batch No: 1720
- Batch No: 3504

Temperature $T$ (°C) from 0 to 600
TENSILE TESTS ON SAP ISML 7% (Euratom results) Ref. 45-46.

Strain $e = f(T)$

$\Delta e_{pu}$: Engineering plastic uniform strain

$\varepsilon_{pb}$: strain at breaking point.

<table>
<thead>
<tr>
<th>Batch No</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
<td>$\Delta$</td>
</tr>
<tr>
<td>1720</td>
<td>$\Delta (1)$</td>
</tr>
<tr>
<td>3504</td>
<td>$\Delta (2)$</td>
</tr>
</tbody>
</table>

Fig.14
TENSILE TESTS ON SAP ISML 10% (Euratom Results) Ref. 45-46

Stress \( S = f(T) \)

\( S_0 \): Engineering maximum tensile stress

\( S_{0.2} \): 0.2 offset yield stress

<table>
<thead>
<tr>
<th>BatchNo</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>(1)</td>
</tr>
<tr>
<td>1754</td>
<td>(2)</td>
</tr>
<tr>
<td>3240</td>
<td>Black</td>
</tr>
</tbody>
</table>
TENSILE TESTS ON SAP ISML 10 %
(Euratom results) ref 45-46.
Strain $e = f(T)$

$\Delta e_{pu}$: Engineering plastic uniform strain.
$+ e_{pb}$: strain at breaking point

<table>
<thead>
<tr>
<th>Batch No</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>$\Delta$ (1) $+$</td>
</tr>
<tr>
<td>1754</td>
<td>$\Delta$ (2) $+$</td>
</tr>
<tr>
<td>3240</td>
<td>$\Delta$ Black $+$</td>
</tr>
</tbody>
</table>

Graph showing strain percentage $e$ (%) vs. temperature $T$ (°C) from 0 to 600°C.
TENSILE TESTS ON SAP ISML 14% (Euratom results) Ref 45-46.
Stress $S = f(T)$

○ $S_{u}$: Engineering maximum tensile stress
☐ $S_{0.2}$: " 0.2 offset yield stress

<table>
<thead>
<tr>
<th>Batch No</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>787/317</td>
<td>(1)</td>
</tr>
<tr>
<td>1244</td>
<td>(2)</td>
</tr>
</tbody>
</table>
TENSILE TESTS ON SAP ISML 14% 
(Euratom results) Ref. 45-46
Strain $\Theta = f(T)$

$\Delta : e_{pu}$ Engineering plastic uniform strain

+ " " strain at breaking point

<table>
<thead>
<tr>
<th>Batch No</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>287/317</td>
<td>+ (1)</td>
</tr>
<tr>
<td>1244</td>
<td>+ (2)</td>
</tr>
</tbody>
</table>

Fig. 18
TENSILE TESTS ON SAP ISML (Euratom Results Ref. 46)

CUMULATIVE CURVES FOR THE FOUR GRADES OF SAP

Maximum Stress $S_u = f(T)$

Specimen Fig. 3 bars $\phi 9.5$ mm

<table>
<thead>
<tr>
<th>Represent.</th>
<th>$%$ $Al_2O_3$</th>
<th>Batch No</th>
<th>fig. no</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP 14%</td>
<td>287/317</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>SAP 10%</td>
<td>280</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>SAP 7%</td>
<td>275</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>SAP 4%</td>
<td>289/291/828</td>
<td></td>
<td>11</td>
</tr>
</tbody>
</table>

$S_u$ (kg/mm$^2$)

$T$ ($^\circ$C)
TENSILE TESTS ON SAP ISML (ISML Results Ref. 22) CUMULATIVE CURVES FOR THE FOUR GRADES OF SAP

Maximum Stress $S = f(T)$

Specimen Fig. 94 machined from extruded bars $\phi \geq 16\text{mm}$
TENSILE TESTS ON SAP ISML (Euratlon Results Ref.46)
CUMULATIVE CURVES FOR THE FOUR GRADES OF SAP.
Engineering 0.2 offset yield Stress = f(T)

Specimen Fig. 3 Bars \( \phi \) 9.5 mm

<table>
<thead>
<tr>
<th>Representation</th>
<th>%Al2O3</th>
<th>Batch No</th>
<th>Fig. n°</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP 14 %</td>
<td></td>
<td>287/317</td>
<td>17</td>
</tr>
<tr>
<td>SAP 10 %</td>
<td></td>
<td>280</td>
<td>15</td>
</tr>
<tr>
<td>SAP 7 %</td>
<td></td>
<td>275</td>
<td>13</td>
</tr>
<tr>
<td>SAP 4 %</td>
<td></td>
<td>289/291/828</td>
<td>11</td>
</tr>
</tbody>
</table>

\( S_{0.2} \) (kg/mm²)
TENSILE TESTS ON SAP ISML (ISML Results Ref. 22) CUMULATIVE CURVES FOR THE FOUR GRADES OF SAP

Engineering 0.2 offset yield Stress = f(T)

Specimen Fig. 4 machined from extruded bars φ ≥ 16mm.
TENSILE TESTS ON SAP ISML (Euratom Results Ref. 46) CUMULATIVE CURVES FOR THE FOUR GRADES OF SAP—Engineering plastic uniform Strain $e_{pu} = f(T)$

<table>
<thead>
<tr>
<th>Representation</th>
<th>$% Al_2O_3$</th>
<th>Batch No</th>
<th>Fig. no</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP 14%</td>
<td>287/317</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>SAP 10%</td>
<td>280</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>SAP 7%</td>
<td>275</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>SAP 4%</td>
<td>289/291/826</td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

Enlarged scale $e_{pu} \%$

Standard scale $e_{pu} \%$

FIG. 23
TENSILE TESTS ON SAP ISML (Euratom Results Ref. 46) CUMULATIVE CURVES FOR THE FOUR GRADES OF SAP Engineering plastic strain at breaking point \( (e_{pb}) = f(T) \)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Fig. 3 Bars ø 9.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Represent.</td>
<td>% Al₂O₃</td>
</tr>
<tr>
<td>SAP 14%</td>
<td>287/317</td>
</tr>
<tr>
<td>SAP 10%</td>
<td>280</td>
</tr>
<tr>
<td>SAP 7%</td>
<td>275</td>
</tr>
<tr>
<td>SAP 4%</td>
<td>289/291/828</td>
</tr>
</tbody>
</table>
TENSILE TESTS ON SAP ISML (ISML Results Ref. 22)
CUMULATIVE CURVES FOR THE FOUR GRADES OF SAP
Engineering plastic strain at breaking point $e_{pb} = f(T)$

Specimen Fig. 94 machined from extruded bars
$d \geq 16 \text{mm}$

FIG. 25
TENSILE TESTS ON SAP ISML (Euratom results Ref. 45-46)
Stress vs. oxide content

Specimen fig. 3 Bars ø 9.5 mm

\[ S_{0.2}(\text{Kg/mm}^2) = f(\% \text{Al}_2\text{O}_3) \]

\[ S_{u}(\text{Kg/mm}^2) = f(\% \text{Al}_2\text{O}_3) \]

\[ T = 200^\circ C \]

\[ T = 300^\circ C \]

\[ T = 400^\circ C \]

\[ T = 500^\circ C \]

\[ T = 600^\circ C \]
TENSILE TESTS ON SAP ISML
(Euratom results Ref. 45-46)

Strain vs oxide content

$e_{pb} = f \% Al_2O_3$

<table>
<thead>
<tr>
<th>%Al$_2$O$_3$</th>
<th>Batch No</th>
<th>From Fig. No</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 %</td>
<td>289/291/822</td>
<td>Mean values of curves (1) and (2)</td>
</tr>
<tr>
<td>7 %</td>
<td>275</td>
<td>FIG 11</td>
</tr>
<tr>
<td>10</td>
<td>280</td>
<td>13</td>
</tr>
<tr>
<td>14 %</td>
<td>287/317</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17</td>
</tr>
</tbody>
</table>

Fig. 11

$e_{pb} = 1(\% Al_2O_3)$
TENSILE TESTS ON SAP ISML (ISML Results Ref. 11)

Tensile properties vs. oxide content
(The values are taken from histograms of Fig. 86-87)

- $\sigma_u$: Engineering maximum tensile stress
- $\sigma_{0.2}$: 0.2 offset yield
- $\varepsilon_{pb}$: Plastic strain at breaking point

Specimen Fig 4
Bars $\Phi \geq 16$ mm
TENSILE TESTS ON SAP ISML 4% after various thermal and mechanical transformations (Euratom results Ref. 27-46)

Batch No 830 Bars ø 16mm

ظرعى S(Kg/mm²)

Θ Su Engineering maximum tensile stress
Ο Σο.2 “ 0.2 offset yield stress

1. Extruded
2. Cold-rolled 92%
3. ” recrystallized 3h 620°C

Test specimen

FIG 29
TENSILE TESTS ON SAP ISML 4%,
various thermal and mechanical transformations
(Euratom results Ref. 27-46)
Batch No 830 bars ø 16 mm
AECL TENSILE SPECIMEN Ref. 33
(Gauge length = 3.9 X diameter)
TENSILE TESTS ON SAP ISML 4%
(A.E.C.L Results Ref. 33)

\[ S = f(T) \]

- \( \bigcirc \) SuEngineering maximum tensile stress
- \( \square \) 0.2 offset yield stress

Specimen Fig 31 SAP manufactured in 1961
TENSILE TESTS ON SAP ISML 4% + \( e_{pb} \) Engineering plastic strain at breaking point

\( e_{pb} = f(T) \)

Specimen Fig 31  SAP made in 1961
TENSILE TESTS ON SAP ISML (AEK Risø Results Ref.41) Tensile properties vs oxide content.

- $S_u$: Engineering maximum tensile stress
- $S_{0.2}$: 0.2 offset yield stress
- $\varepsilon_{pb}$: Plastic strain at breaking point

Specimen gauge length: 10x diameter

Bars $\Phi$ 16 mm

$T=20^\circ C$

$T=400^\circ C$
COMPRESSION TESTS ON SAP ISML

Engineering maximum tensile stress for various oxide contents $S_u = f(T)$
(Euratom results Ref. 32)

Batch No
- S.A.P. 14% 1243
- 10% 1702
- 7 1723
- 4 1346

$S_u$ (Kg/mm) $^2$ vs $T$ (°C)
COMPRESSION TESTS ON SAP ISML
(Euratom results Ref. 32)

$S_{0.2} = f(T)$

$S_{0.2}$ Engineering 0.2 offset yield stress

- S.A.P. 14% 1243
- 10% 1782
- 7% 1723
- 4% 1346

Specimen: cylinders $\phi 4\text{ mm}$, $l_0 = 4\text{ mm}$

FIG. 36
COMPRESSION TESTS ON SAP ISML
(Euratom Results Ref. 32)

\[ \varepsilon_{pu} = f(T) \]

\( \varepsilon_{pu} \): Engineering plastic uniform strain
Specimen: cylinder \( \varnothing 4 \text{ mm} \)  \( l_s = 4 \text{ mm} \)

Batch

- S.A.P. 14% 1243
- 10% 1782
- 7% 1723
- 4% 1346

FIG. 37
SEMI-FINISHED PRODUCTS
CREEP TESTS
Fig. 38

EURATOM CREEP SPECIMEN (FL 2)

Fig. 39

ISML CREEP SPECIMEN (Ref. 9)
STRESS RUPTURE TESTS AT 400°C AND 460°C ON SAP ISML 4 %
(Euratom and ISML Results)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Symbol</th>
<th>Batch No</th>
<th>Reference</th>
<th>Specimen</th>
<th>§ Diam. mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>460°C</td>
<td>○</td>
<td>289</td>
<td>45-46</td>
<td>FIG 38</td>
<td>9.5</td>
</tr>
<tr>
<td>400°C</td>
<td>●</td>
<td>380-381</td>
<td>8-45-46</td>
<td>FIG 39</td>
<td>21</td>
</tr>
</tbody>
</table>

Life, hours

Fig. 40
STRESS- RUPTURE TESTS on SAP ISML 7% at 400°C and 460°C (Euratom and ISML results)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Temperat.</th>
<th>Batch No</th>
<th>Reference</th>
<th>Specimen</th>
<th>8 Bars (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euratom tests</td>
<td>○</td>
<td>460°C</td>
<td>275</td>
<td>45-46</td>
<td>FIG. 38</td>
</tr>
<tr>
<td>ISML tests</td>
<td>●</td>
<td>400°C</td>
<td>393-394</td>
<td>8-45-46</td>
<td>FIG. 39</td>
</tr>
</tbody>
</table>

FIG. 38

FIG. 39
STRESS RUPTURE TESTS AT 420°C ON SAP ISML 7/4
(Euratom Results) Ref. 51
Batch No. 1722 Specimen Fig. 38 Bars φ 9.5 mm
**STRESS RUPTURE TESTS AT 460°C ON SAP 15ML 7%**

Euratom results Ref. 51

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Batch No</th>
<th>Fig</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>275</td>
<td>41</td>
<td>8</td>
</tr>
<tr>
<td>+</td>
<td>1067</td>
<td>51</td>
<td>49</td>
</tr>
<tr>
<td>Δ</td>
<td>1721</td>
<td>51 bis</td>
<td>51</td>
</tr>
<tr>
<td>○</td>
<td>1722</td>
<td>51 ter</td>
<td>51</td>
</tr>
<tr>
<td>□</td>
<td>3552</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Specimen Fig 38  Bars 9.5 mm diameter

Graph showing stress rupture test results with life hours on the x-axis and stress (Kg/mm²) on the y-axis.
HISTOGRAMS OF ELONGATIONS DURING CREEP TESTS AT 460°C ON SAP ISML 7% (Euratom Results Ref. 51) Specimen Fig. 38
Bars Ø 9.5 Batch No 1722

Quantity of samples

Elongation 1h after loading

Elongation at rupture

Fig. 44
STRESS RUPTURE TESTS AT 400°C AND 460°C ON SAP ISML 10%
(Euratom and ISML Results)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Temperature</th>
<th>Batch No</th>
<th>Reference</th>
<th>Specimen</th>
<th>Bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>•</td>
<td>400°C</td>
<td>307</td>
<td>45-46</td>
<td>Fig. 38</td>
<td>9.5</td>
</tr>
<tr>
<td>•</td>
<td>460°C</td>
<td>408-409</td>
<td>44-45</td>
<td>Fig. 39</td>
<td>21</td>
</tr>
</tbody>
</table>

Fig. 38
Fig. 39
STRESS RUPTURE TESTS AT 400°C AND 460°C ON SAP ISML 14 %
(Euratom and ISML Results)

<table>
<thead>
<tr>
<th>symbol</th>
<th>Temp.:</th>
<th>Batch No</th>
<th>Reference</th>
<th>Specimen</th>
<th>bar (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euratom tests</td>
<td>460°C</td>
<td>313-314/1</td>
<td>46</td>
<td>Fig. 38</td>
<td>95</td>
</tr>
<tr>
<td>ISML tests</td>
<td>400°C</td>
<td>415</td>
<td>8-46</td>
<td>Fig. 39</td>
<td>21</td>
</tr>
</tbody>
</table>

Life, hours - 

Temperature 400°C

Temperature 460°C
STRESS RUPTURE TESTS ON SAP 7% (Euratom results)

Influence of temperature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Batch No</th>
<th>Test temp.</th>
<th>from fig</th>
<th>ref.</th>
<th>$\sigma_{bars}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>393-394</td>
<td>400</td>
<td>41</td>
<td>8-15-46</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>1722</td>
<td>420</td>
<td>42</td>
<td>51</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>1957-1722-3552</td>
<td>460</td>
<td>43</td>
<td>51</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>275</td>
<td>460</td>
<td>41</td>
<td>45-46</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Fig. 47
STRESS RUPTURE TESTS AT 400°C ON SAP ISML
Cumulative diagrams (ISML Results)
Influence of oxide content

<table>
<thead>
<tr>
<th>%Al₂O₃</th>
<th>Batch No</th>
<th>from ref.</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>380-381</td>
<td>46</td>
<td>74-45-46</td>
</tr>
<tr>
<td>7</td>
<td>383-384</td>
<td>41</td>
<td>74-45-46</td>
</tr>
<tr>
<td>10</td>
<td>409-409</td>
<td>45</td>
<td>74-45-46</td>
</tr>
<tr>
<td>14</td>
<td>415</td>
<td>46</td>
<td>79-46</td>
</tr>
</tbody>
</table>

Bars $\phi$ 21mm
STRESS RUPTURE TESTS AT 460°C ON SAP ISML
Cumulative diagrams (Euromont Results)
Influence of oxide content
Specimen Fig. 38 Bars φ 21

STRESS PRODUCING 0.1 % STRAIN
(ISML Results Ref. 7)

Fig. 50

T = 400°C

Kg/mm²

S.A.P. ISML 7%
S.A.P. ISML 10%
S.A.P. ISML 14%
S.A.P. ISML 4%

Time (hours)
ELONGATION AFTER 1000 hours OF CREEP TESTS AT 400°C
(ISML Results Ref. 6)

Bars 421mm
Specimen Fig. 39

+Extrapolated values

S.A.P. ISML 14%
S.A.P. ISML 10%
S.A.P. ISML 7%
S.A.P. ISML 4%
STRESS RUPTURE TESTS AT 460°C ON THERMAL TREATED SAP 4%
(Euratom Results) Ref. 48

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Thermal treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>• A</td>
<td>600°C 23h</td>
</tr>
<tr>
<td>• B</td>
<td>640°C 1584h</td>
</tr>
<tr>
<td>+ C</td>
<td>640°C 3000h</td>
</tr>
<tr>
<td>- D</td>
<td>none none</td>
</tr>
</tbody>
</table>

Specimen Fig 38 Bars φ 95mm
STRESS-RUPTURE TEST AT 460°C on SAP ISML 7%
(Euroton results Ref.43 Batch No 1067)
Influence of thermal cycling

- Tests at 460°C without thermal cycling
- Tests with thermal cycling (4 cycles in 24 hours between 340 and 460°C)

Test specimen Fig 38 (bars ø 95mm)
BATTLE INSTITUTE FRANKFURT CREEP SPECIMEN(FL1)
STRESS RUPTURE TESTS AT 460°C ON SAP ISML 4%.
(Battelle Institut Frankfurt Results) Ref. 47

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Batch N.</th>
</tr>
</thead>
<tbody>
<tr>
<td>•</td>
<td>890</td>
</tr>
<tr>
<td>o</td>
<td>645</td>
</tr>
</tbody>
</table>

Specimen Fig 54 Bars φ 21 mm
HISTOGRAMS OF ELONGATIONS DURING CREEP TESTS AT 460°C ON SAP ISML 4%
(Battelle Institut Frankfurt Results Ref. 47) Specimen Fig. 54 Bars ø 21mm Batch No 645-890

Quantity of samples

Elongation 10 hours after loading

Elongation at rupture

Quantity of samples
HISTOGRAMS OF ELONGATIONS DURING CREEP TESTS AT 460°C ON SAP ISML 7 %
(Battelle Institut Frankfurt Results Ref. 47) Specimen Fig. 54 Bars ø21 mm

Quantity of samples

Elongation 10 hours after loading

Elongation at rupture

Batch No
{551 - 552
906 - 907-908-909
1300 - 1301

Quantity of samples

ε_{10h} %

ε_r %

Fig. 58
RODS CREEP (AECL)
AECL CREEP SPECIMEN Ref. 33

R = 0.15

Dimensions:
- OD: 30.7 mm
- ID: 5.48 mm
- Length: 29 mm
- 12.7 mm
d- 6.01 mm
d- 7.36 mm
### Stress Rupture Tests Performed at AECL

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimens</th>
<th>Reference</th>
<th>Symbol</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 °C</td>
<td>500 bars</td>
<td>Specimen Fig. 59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600 °C</td>
<td>600 bars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 °C</td>
<td>700 bars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800 °C</td>
<td>800 bars</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Results**: 9.12% 7% 4%

**Fig. 60**
COMPARISON OF RESULTS FROM DIFFERENT LABORATORIES
Comparison of results from different laboratories.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Batch No</th>
<th>from No</th>
<th>ref</th>
<th>Symbol</th>
<th># bars mm</th>
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</thead>
<tbody>
<tr>
<td>EURATOM</td>
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<td></td>
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<tr>
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<td>38</td>
<td>289</td>
<td>40</td>
<td>45-46</td>
<td>9.5</td>
</tr>
<tr>
<td>7</td>
<td>38</td>
<td>275</td>
<td>41</td>
<td>45-46</td>
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<tr>
<td>7</td>
<td>1061725</td>
<td>0200-352</td>
<td>43</td>
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<td>51</td>
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<tr>
<td>4</td>
<td>54</td>
<td>645</td>
<td>55</td>
<td>47</td>
<td>21</td>
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<td></td>
<td></td>
<td>880</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1065-1721</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1300-1301</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 61**

**Graph**
- Graph showing stress-rupture tests on SAP ISML 4% and 7%.
- Comparison of results from different laboratories.
- Key: EURATOM and BATTELLE INSTITUT FRANKFURT.
- Life hours range from 10000 to 20000.
ISML RELAXATION SPECIMEN (Ref. ISML Drawing PDC 27/1)

EURATOM RELAXATION SPECIMEN (Ref. 57)
RELAXATION TESTS AT 20°C ON SAP ISML 7%

Euratom Results
Test specimen Fig. 3

Batch No ref. symbol
2455 58 □
1723 60 □

σ Kg/mm²

Time (hours)
HIGH TEMPERATURE RELAXATION TESTS ON SAP ISML

Euratom results

<table>
<thead>
<tr>
<th>Batch No.</th>
<th>%Al₂O₃</th>
<th>Temperat. (°C)</th>
<th>thermal treatment</th>
<th>Specimen</th>
<th>Symbol</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2455</td>
<td>7</td>
<td>450</td>
<td>none</td>
<td>3</td>
<td>•</td>
<td>58</td>
</tr>
<tr>
<td>2455</td>
<td>7</td>
<td>450</td>
<td>－</td>
<td>3</td>
<td>•</td>
<td>58</td>
</tr>
<tr>
<td>2455</td>
<td>7</td>
<td>450</td>
<td>－</td>
<td>3</td>
<td>•</td>
<td>58</td>
</tr>
<tr>
<td>2455</td>
<td>7</td>
<td>450</td>
<td>－</td>
<td>3</td>
<td>•</td>
<td>58</td>
</tr>
<tr>
<td>2455</td>
<td>7</td>
<td>450</td>
<td>－</td>
<td>3</td>
<td>•</td>
<td>58</td>
</tr>
<tr>
<td>2455</td>
<td>7</td>
<td>450</td>
<td>－</td>
<td>3</td>
<td>•</td>
<td>58</td>
</tr>
<tr>
<td>1743</td>
<td>7</td>
<td>480</td>
<td>160h/60°C</td>
<td>61</td>
<td>□</td>
<td>57</td>
</tr>
<tr>
<td>1743</td>
<td>7</td>
<td>466</td>
<td>3h/610°C</td>
<td>61</td>
<td>■</td>
<td>57</td>
</tr>
<tr>
<td>1527</td>
<td>10</td>
<td>450</td>
<td>5h/600°C</td>
<td>61</td>
<td>x</td>
<td>57</td>
</tr>
<tr>
<td>1527</td>
<td>10</td>
<td>450</td>
<td>16h/600°C</td>
<td>61</td>
<td>•</td>
<td>57</td>
</tr>
<tr>
<td>1723</td>
<td>7</td>
<td>450</td>
<td>none</td>
<td>3</td>
<td>B</td>
<td>60</td>
</tr>
</tbody>
</table>
RELAXATION TESTS AT 450°C ON SAP ISML 7%  
Euratom results Ref. 80 Batch No. 1723
RELAXATION TESTS AT 450°C ON SAP ISML 7%
ISML Results Ref 21 Batch No 2622
Test specimen Fig 62

Strain (%) symbol
0.165 x
0.120 +
0.050 *

Time (hours)
0.01 0.1 1 10 100 1000

Strain Kg/mm²
0 1 2 3 4 5

Fig 62
SEMI-FINISHED PRODUCTS

IMPACT STRENGTH TESTS
CHARPY SPECIMEN FOR IMPACT STRENGTH TEST

Fig. 67

Fig. 68

IMPACT STRENGTH VS TEMPERATURE FOR SAP ISML 4% AND 7%
(ISML Results Ref. 9-10-22-45-46)

Impact characteristics

speed (m/sec) energy (mKg)

- S33 30
- 389 15.9
- 254 7.3

SAP ISML 4% Batch 91

SAP 7% Batch 86
SEMI-FINISHED PRODUCTS

HARDNESS
VICKERS MICRO AND MACRO HARDNESS AT 20°C ON SAP ISML AND ALUMINIUM A5 (Euratom Results Ref. 28) SAP PRODUCED ON MAX 1961

![Micro-Hardness Graph](image1)

Micro-Hardness  
(mean value of 10 measurements on the same specimen)  
P=100g  t=10s.

![Macro-Hardness Graph](image2)

Macro-Hardness from fig 71 (mean value of 3 measurements on the same specimen)

<table>
<thead>
<tr>
<th>% Al₂O₃</th>
<th>Load (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2.4</td>
<td>1</td>
</tr>
<tr>
<td>3.7</td>
<td>2</td>
</tr>
<tr>
<td>8.3</td>
<td>1</td>
</tr>
<tr>
<td>11.9</td>
<td>2</td>
</tr>
</tbody>
</table>

VICKERS MICROHARDNESS OF SAP ISML VS. TEMPERATURE  
(Euratom Results Ref. 28 bis)

![Temperature Graph](image3)

Characteristics of the material

<table>
<thead>
<tr>
<th>Symbol</th>
<th>% Al₂O₃</th>
<th>Batch No</th>
<th>Type of starting powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>4</td>
<td>1733</td>
<td>A.I.A.G</td>
</tr>
<tr>
<td>▲</td>
<td>7</td>
<td>1673</td>
<td>Eckart-Werke</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1730</td>
<td>n</td>
</tr>
</tbody>
</table>

Specimens machined from rods 42 mm (extrusion ratio 3.6)

In black results from Fig.69
BRINNEL MACRO-HARDNESS AT 20°C ON SAP ISML
(ISML Results Ref. 2-3-4)

Test condition
ball \( \phi 2.5 \text{ mm} \)
load 62.5 Kg
time of application: 30 s

Batch No

<table>
<thead>
<tr>
<th>% ( \text{Al}_2\text{O}_3 )</th>
<th>( \phi \text{ bar (mm)} )</th>
<th>4</th>
<th>7</th>
<th>10</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13</td>
<td>96</td>
<td>95</td>
<td>113</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>118</td>
<td>121</td>
<td>122</td>
<td>127</td>
</tr>
</tbody>
</table>

Number of measurements on each specimen

<table>
<thead>
<tr>
<th>Symbol</th>
<th>( \phi \text{ bar (mm)} )</th>
<th>Number of measurements on each specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bigcirc )</td>
<td>13</td>
<td>3 to 6</td>
</tr>
<tr>
<td>( \triangle )</td>
<td>14</td>
<td>2</td>
</tr>
</tbody>
</table>

BRINNEL MACRO-HARDNESS OF SAP ISML VS. TEMPERATURE
(Euratom results Ref. 30 bis)
(bars \# 14 to 22 mm)

Symbol | % \( \text{Al}_2\text{O}_3 \) | Load (Kg.)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bigcirc )</td>
<td>4.15</td>
<td></td>
</tr>
<tr>
<td>( \bigtriangleup )</td>
<td>8.40</td>
<td>31.2</td>
</tr>
<tr>
<td>( \bigtriangledown )</td>
<td>11.65</td>
<td></td>
</tr>
<tr>
<td>( \bigtriangledown )</td>
<td>14.65</td>
<td></td>
</tr>
</tbody>
</table>

(\( \text{In black point, from Fig. 70)} \).
(\( \text{Load 15.6 Kg.} \).
BRINNEL MACRO-HARDNESS OF SAP ISML 7 AND 14% VS. TEMPERATURE
(ISML Results Ref. 21B)
VICKER HARDNESS AT 20° C ON SAP ISML VS DEFORMATION RATIO
(Euratom Results Ref.56) Influence of cold deformation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>%Al₂O₃</th>
<th>Load on the Vickers Indenter (Kg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>11.9</td>
<td>2</td>
</tr>
<tr>
<td>△</td>
<td>8.3</td>
<td>1</td>
</tr>
<tr>
<td>●</td>
<td>3.7</td>
<td>2</td>
</tr>
<tr>
<td>▲</td>
<td>2.4</td>
<td>1</td>
</tr>
<tr>
<td>+</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

$H_v \text{ Kg/mm}^2$

$\text{deformation \%}$
VICKERS HARDNESS AT 20°C ON SAP ISML AFTER DIFFERENT RATES OF COLD WORK VS. ANNEALING TEMPERATURE (Euratom results Ref. 56)

<table>
<thead>
<tr>
<th>Symbole</th>
<th>Cold_work</th>
</tr>
</thead>
<tbody>
<tr>
<td>o</td>
<td>95</td>
</tr>
<tr>
<td>△</td>
<td>90</td>
</tr>
<tr>
<td>•</td>
<td>74</td>
</tr>
<tr>
<td>△</td>
<td>53</td>
</tr>
<tr>
<td>+</td>
<td>22</td>
</tr>
<tr>
<td>•</td>
<td>0</td>
</tr>
</tbody>
</table>

SAP specimens 3.7% Al₂O₃ Cold rolled.
VICKERS HARDNESS AT 20°C ON COLD WORKED SAP ISML
VS. ANNEALING TEMPERATURE
(Euratom results Ref. 56)

Cold rolled S.A.P.(rate 95%)

<table>
<thead>
<tr>
<th>Symbole</th>
<th>%Al_2O_3</th>
<th>Load (Kg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>o</td>
<td>11.9</td>
<td>2</td>
</tr>
<tr>
<td>△</td>
<td>8.3</td>
<td>1</td>
</tr>
<tr>
<td>•</td>
<td>3.7</td>
<td>2</td>
</tr>
<tr>
<td>▲</td>
<td>2.4</td>
<td>1</td>
</tr>
</tbody>
</table>

Hardness of annealed specimens (from Fig. 71)

Fig. 73

annealing temperature

Hv
Kg/mm^2

0 200 300 400 500 600 700

0 50 100

100 Hv Kg/mm^2

100
**Fig. 74**

ISML SPECIMEN FOR ROTATING BENDING TESTS AT 20°C AND 400°C
(Ref. 8)

**Fig. 75**

ROTATING BENDING TESTS AT 20°C AND 400°C ON SAP ISML 4¼
(ISML Results Ref 8-4-6)

Graph showing the relationship between stress (S) and the number of cycles (N) for different temperatures (20°C and 400°C) across various batch numbers (333, 362, 364) with a rotating speed of 3000 r.p.m.
ROTATING BENDING TESTS AT 20°C AND 400°C ON SAP ISML 7% (ISML Results Ref. 12)

Fig. 76

- Influence of temperature
- Batch No: 700, 701, 1111, 1112
- Rotating speed: 3000 r.p.m
- Number of cycles: N

ROTATING BENDING TESTS AT 20°C AND 400°C ON SAP ISML 10% (ISML Results Ref. 11)

Fig. 77

- Influence of temperature
- Batch No: 903, 1016
- Rotating speed: 3000 r.p.m
- Number of cycles: N

Graphs showing the influence of temperature on the bending strength (S in Kgf/mm²) at different batches and rotating speeds.
Influence of temperature

Batch No 1136-1137
Bars φ 14 mm
Rotating speed 3000 r.p.m

Rotating Bending Tests at 20°C and 400°C on SAP ISML (CUMULATIVE DIAGRAMS)
(ISML Results Ref. 12-46)

Rotating speed
3000 r.p.m
ROTATING BENDING TESTS AT 20°C ON NOTCHED SPECIMENS OF SAP ISML 4% (ISML Results) Influence of notch

- Unnotched specimen (Fig. 81)
- "V" notch (Fig. 80)
- "U" notch (Fig. 80)

Rotating speed 11,500 r.p.m.
Specimens machined out of bars φ 14 mm

Batch No.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Batch No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>96</td>
</tr>
<tr>
<td>80&quot;V&quot;</td>
<td>363</td>
</tr>
<tr>
<td>80&quot;U&quot;</td>
<td>112</td>
</tr>
<tr>
<td>Ref.</td>
<td>2-46</td>
</tr>
</tbody>
</table>

Number of cycles N

Fig. 82

ROTATING BENDING TESTS AT 20°C ON NOTCHED SPECIMENS OF SAP ISML 7% (ISML Results) Influence of notch

- Unnotched specimen (Fig. 81)
- "V" notch (Fig. 80)
- "U" notch (Fig. 80)

Rotating speed 11,500 r.p.m.
Specimens machined out of bars φ 14 mm

Batch No.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Batch No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>95</td>
</tr>
<tr>
<td>80&quot;V&quot;</td>
<td>335</td>
</tr>
<tr>
<td>80&quot;U&quot;</td>
<td>113</td>
</tr>
<tr>
<td>Ref.</td>
<td>2-46</td>
</tr>
</tbody>
</table>

Number of cycles N

Fig. 83
ROTATING BENDING TESTS AT 20°C ON NOTCHED SPECIMENS
OF SAP ISML 10% (ISML Results)
Influence of notch.

Fig. 84

Rotating speed 11500 r.p.m.
Specimen machined out of bars φ14 mm

Batch No

Specimen
Fig.
81
80°U,

Batch No
65-66
114

Ref.
2
3

Number of cycles

N

Rotating speed 11500 r.p.m.
Specimen machined out of bars φ14 mm

Batch No

Specimen
Fig.
81
80°U,

Batch No
77-78
115

Ref.
2
3
SEMI-FINISHED PRODUCTS

EVOLUTION OF ROD PRODUCTION
HISTOGRAMS OF THE TENSILE PROPERTIES AT 20°C OF SAP ISML (Different extrusion ratios)
ISML Results (Ref. 11)

Batches from 28 to 503

Batches from 26 to 1019

Batches from 24 to 1007

Batches from 88 to 825

Mean values

S.A.P. 14%

S.A.P. 10%

S.A.P. 7%

S.A.P. 4%
HISTOGRAMS OF THE TENSILE PROPERTIES AT 400°C OF SAP ISML (Different extrusion ratios)
ISML Results (Ref 11)

Batches from
28 to 503

26 to 1019

24 to 1007

88 to 825

S.A.P. 14%
S.A.P. 10%
S.A.P. 7%
S.A.P. 4%

Mean values

\( \sigma_{cc} \)

\( \mu \)

\( \rho_{r} \)

\( \Gamma \)

\( \Omega \)

\( \eta \)

\( \lambda \)

\( \chi \)

\( \theta \)

\( S_{u} \)

\( S_{0.2} \)

\( e_{pb} \)

FIG. 87
TENSILE TESTS AT 450°C ON BARS OF SAP ISML 7%
(ISML Results Ref. 35 Batch No 1810 to 2623)

Histograms of Maximum Tensile Stress ($S_u$) and plastic strain at breaking point.

Mean value $7.6 \text{ Kg/mm}^2$

Mean value 4.4 %
TENSILE TESTS ON SAP ISML 7%

Engineering 0.2 offset yield stress as a function of Batch Number
(Extruded bars, Batch number from 24 to 2623)

- Test temperature 400°C
- Test temperature 450°C

![Graph showing tensile test results for SAP ISML 7%](image-url)
TENSILE TESTS ON SAP ISML 7%

Engineering maximum tensile stress as a function of Batch Number.

(Extruded bars Batch Number from 24 To 2623)

ISML Results Ref. 35

\[ S_e (\text{Kg/mm}^2) \]

Test temperature: 400°C

Years

Powder AIAG  AIAG + Eckart Werk  Powder Eckart Werk
TENSILE TESTS ON SAP ISML 7% 
Engineering plastic strain at breaking point as a function of Batch Number.
(Extruded bars, Batch number from 24 to 2623)
ISML Results Ref. 35

Test temperature 400°C

+ 450°C
SEMI-FINISHED PRODUCTS

PHYSICAL PROPERTIES
YOUNG'S MODULUS AT 20°C OF SAP ISML VS OXIDE CONTENT

Static method (tensile)

- ISML (Ref 9)
- Euratom (Ref 27)

Dynamic method (internal damping)

- ISML (Ref 3-24)
- Euratom (Ref 29)

%Al₂O₃ | 4 7 10 14
---|---
Eurat Batch | 291 300 321 316
| 95 95 16 16
ISML Batch | 273 276 281 286
| 16 16 16 16

%Al₂O₃ vs E (Kg/mm²)

Batch:
- ISML
- Euratom

Materials:
- ISML (Ref 9)
- Euratom (Ref 27, 29)

Graph shows the relationship between %Al₂O₃ and Young's Modulus E at 20°C for SAP ISML and Euratom materials.
YOUNG'S MODULUS OF SAP ISML VS TEMPERATURE

**Static Method (Tensile)**

- ISML Results (with Martens extensometer)
- EURATOM Results (deflection method Ref. 30)

**Dynamic Method (Internal Damping)**

- EURATOM Results (Ref. 29-46)

### Table: %Al₂O₃

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>ISML</th>
<th>Eurat.</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch 1</td>
<td>1215</td>
<td>Ref 30-46</td>
<td></td>
</tr>
<tr>
<td>Batch 2</td>
<td>273</td>
<td>276</td>
<td>281</td>
</tr>
<tr>
<td>ISML</td>
<td>6-46</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

### Graph:
- E (Kg/mm²) vs. T°C (°C)
- Dynamic Method (Internal Damping)

**Fig. 93**
MEAN COEFFICIENT OF LINEAR THERMAL EXPANSION OF SAP ISML VS. OXIDE CONTENT
(Euratom Results Ref. 25)

Results obtained parallel to the extrusion direction

- Dilatometer "Adamel,, 55(K300)
- " " " " (K150)

% Al₂O₃

cm/cm°C·10⁻⁶
ELECTRICAL RESISTIVITY AT 20°C OF SAP ISML WITH VARIOUS OXIDE CONTENTS (Euratom and ISML results)

<table>
<thead>
<tr>
<th>Euratom results</th>
<th>Conventional signs</th>
<th>Material</th>
<th>Ref No</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Aluminium A 5 N</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>•</td>
<td>SAP(Al₂O₃ average of 3 analyses)</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>Aluminium 99.99 %</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>SAP (real Al₂O₃ content)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ISML results</th>
<th>Material</th>
<th>Ref No</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Aluminium 99.99 %</td>
<td>9</td>
</tr>
<tr>
<td>×</td>
<td>SAP(Al₂O₃ nominal value)</td>
<td>26</td>
</tr>
</tbody>
</table>

Fig. 95
ELECTRICAL RESISTIVITY OF SAP ISML VS TEMPERATURE
(Euratom Results, Ref. 54)

Fig. 96

(Results obtained parallel to the extrusion direction)

- S.A.P. 14%
- S.A.P. 10%
- S.A.P. 7%
- S.A.P. 4%
- Aluminium 99.99%

<table>
<thead>
<tr>
<th>% Al₂O₃</th>
<th>Nominal content</th>
<th>Measured content</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>4.3</td>
<td>8.9</td>
<td>10.2</td>
</tr>
</tbody>
</table>

SAP manufactured in 1963

ELECTRICAL RESISTIVITY OF SAP ISML VS TEMPERATURE (ISML Results, Ref. 9-26)

Fig. 97

Specimens machined out of extruded flat bars (30x25 mm) annealed 2h/500°C
(Results obtained parallel to the extrusion direction)

- S.A.P. 14%
- S.A.P. 10%
- S.A.P. 7%
- S.A.P. 4%
- Aluminium 99.995%

<table>
<thead>
<tr>
<th>% Al₂O₃</th>
<th>symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>

Batch No 252 258 261 262
ELECTRICAL RESISTIVITY AT 100°C AND 500°C OF SAP ISML VS. OXIDE CONTENT
(Euratom Results Ref 54)

Results obtained parallel (1) and perpendicular (2) to the extrusion direction

<table>
<thead>
<tr>
<th>% Al₂O₃</th>
<th>Nominal Content</th>
<th>Measured content</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.3</td>
<td>4.7</td>
</tr>
<tr>
<td>7</td>
<td>6.9</td>
<td>7.0</td>
</tr>
<tr>
<td>10</td>
<td>10.7</td>
<td>10.7</td>
</tr>
<tr>
<td>14</td>
<td>14.1</td>
<td>14.1</td>
</tr>
</tbody>
</table>

SAP manufactured in 1963

FIG.98
<table>
<thead>
<tr>
<th>Material</th>
<th>Batch No</th>
<th>symbol</th>
<th>Number of specimens</th>
<th>direction of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI99.999%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAP 4%</td>
<td>1733</td>
<td>+</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SAP 7%</td>
<td>3448</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SAP 10%</td>
<td>3240</td>
<td>X</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>SAP 14%</td>
<td>1586</td>
<td>■</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Method: Stationary measurement with axial Flow

Reference sample: Armco Iron
**THERMAL CONDUCTIVITY AT 100°C AND 500°C OF SAP TSML**

(Euratom Results Ref. 54)

**Fig: 100**

- **Material:** SAP manufactured in 1963
- **Method:** Stationary method with axial flow
- **Results:** obtained parallel to the extrusion direction

**Thermal Conductivity of SAP TSML vs Temperature**

(ISML Results)

**Fig: 101**

- **SAP Material:** cylindrical specimens
  - L = 170mm S = 100mm machined out of bars φ 21mm
- **Method:** American Bureau of Standards Ref. 44
- **Reference Materials:**
  - Aluminium 99.995% (Ref. 4)
  - $K_{Al} = 0.53$ cal/s cm °C between 200 °C and 400 °C (Ref. 9)
- **Results:** obtained parallel to the extrusion direction
THERMAL CONDUCTIVITY AT 500°C OF SAP ISML VS OXIDE CONTENT
(Euratom Results Ref. 54)

### Fig. 102

<table>
<thead>
<tr>
<th>Designation of material</th>
<th>% Al₂O₃ (in weight)</th>
<th>Symbol</th>
<th>Direction of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium 99.98%</td>
<td></td>
<td>+</td>
<td>parallel to extrusion</td>
</tr>
<tr>
<td>S.A.P. 4%</td>
<td>4.3</td>
<td>□</td>
<td>perpendicular</td>
</tr>
<tr>
<td>S.A.P. 7%</td>
<td>6.9</td>
<td>•</td>
<td>parallel</td>
</tr>
<tr>
<td>S.A.P. 10%</td>
<td>10.2</td>
<td>□</td>
<td>parallel</td>
</tr>
<tr>
<td>S.A.P. 14%</td>
<td>14.1</td>
<td>△</td>
<td>perpendicular</td>
</tr>
</tbody>
</table>

SAP manufactured in 1963
Stationary method with axial flow

THERMAL CONDUCTIVITY AT 100°C OF SAP ISML VS OXIDE CONTENT
(Euratom Results Ref. 54)

### Fig. 103

<table>
<thead>
<tr>
<th>Designation of material</th>
<th>% Al₂O₃ (in weight)</th>
<th>Symbol</th>
<th>Direction of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium 99.99%</td>
<td></td>
<td>+</td>
<td>parallel to extrusion</td>
</tr>
<tr>
<td>S.A.P. 4%</td>
<td>4.3</td>
<td>□</td>
<td>perpendicular</td>
</tr>
<tr>
<td>S.A.P. 7%</td>
<td>6.9</td>
<td>•</td>
<td>parallel</td>
</tr>
<tr>
<td>S.A.P. 10%</td>
<td>10.2</td>
<td>□</td>
<td>parallel</td>
</tr>
<tr>
<td>S.A.P. 14%</td>
<td>14.1</td>
<td>△</td>
<td>perpendicular</td>
</tr>
</tbody>
</table>

SAP manufactured in 1963
Stationary method with axial flow
DENSITY OF SAP ISML VS OXIDE CONTENT
(AEK Risö Results Ref. 99-41)

FIG. 104A

<table>
<thead>
<tr>
<th>Oxide cont.</th>
<th>3.9</th>
<th>7.1</th>
<th>10.0</th>
<th>14.2</th>
<th>symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch No</td>
<td>1220</td>
<td>1221</td>
<td>1222</td>
<td>1223</td>
<td></td>
</tr>
<tr>
<td>from fig 104</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TENSILE TESTS ON SMOOTH TUBES OF SAP ISML (ISML Results Ref. 22-31) Mechanical Properties vs. oxide content.

$S_u = f(\% \text{Al}_2\text{O}_3)$ at $20^\circ C$ and $450^\circ C$

1. Extruded bars
2. Extruded tubes annealed $2h / 550^\circ C$
3. Cold-drawn tubes ($H = 30\%$) annealed $2h / 550^\circ C$
TENSILE TESTS ON SMOOTH TUBES OF SAP ISML (ISML Results Ref. 22-31)

Mechanical Properties vs oxide content.

\[ S_{0.2} = f \left( \% \text{Al}_2\text{O}_3 \right) \text{ at } 20^\circ \text{C and } 450^\circ \text{C} \]

1. Extruded bars
2. Extruded tubes annealed 2 h / 550°C
3. Cold-drawn tubes (H = 30%) annealed 2 h / 500°C
TENSILE TESTS ON SMOOTH TUBES OF SAP ISML (ISML Results Ref 22-34)
Mechanical Properties vs. oxide content.

\[ \varepsilon_{pb} = f(\% \text{ Al}_2\text{O}_3) \text{ at } 20^\circ\text{C} \text{ and } 450^\circ\text{C} \]

1. Extruded bars
2. Extruded tubes annealed 2h/550°C
3. Cold-drawn tubes (H= 30%) annealed 2h/550°C

FIG. 107
STRESS RUPTURE TESTS UNDER INTERNAL GAS PRESSURE ON SMOOTH TUBES OF SAP ISML 4% (ISML Results)

Influence of temperature

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Batch No</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>400°C Tests</td>
<td>374-375</td>
<td>8</td>
</tr>
<tr>
<td>450°C Tests</td>
<td>440</td>
<td>10</td>
</tr>
</tbody>
</table>

P: Burst pressure

$\sigma_t$: Tangential stress

Tubes $\Phi 13.1 \times 14.7$ Annealed 2 h at 500°C

Life (hours)
STRESS RUPTURE TESTS UNDER INTERNAL GAS PRESSURE ON SMOOTH TUBES OF SAP ISML 4% AT 450°C
(Euratom Results Ref. 52)

$\sigma_T$ (Tangential stress) Kg/mm$^2$

<table>
<thead>
<tr>
<th>Batch No</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>440</td>
<td>⋄</td>
</tr>
<tr>
<td>441</td>
<td>⥾</td>
</tr>
</tbody>
</table>

Fig. 109

Life (hours)
STRESS RUPTURE TESTS UNDER INTERNAL GAS PRESSURE ON SMOOTH TUBES OF SAP ISML 7% (ISML Results)

<table>
<thead>
<tr>
<th>Batch No</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>400°C Tests</td>
<td>448</td>
</tr>
<tr>
<td>450°C Tests</td>
<td>450</td>
</tr>
</tbody>
</table>

P: Burst pressure
Qt: Tangential stress

Fig. 110
STRESS RUPTURE TESTS UNDER INTERNAL GAS PRESSURE ON SMOOTH TUBES OF SAP ISML 7% AT 400°C
(ISML Results)

Influence of fabrication process

GT: Tangential stress
P: Burst pressure for 13.1x14.7 Tubes

Symbol | fabricat. | diameters mm | Batch No | Ref.
--- | --- | --- | --- | ---
□ | Extrusion | 16x14 | 1178 | 15
○ | Cold-drawing | 13.1x14.7 | prod. 1961 | 7. 15
△ | cold-draw and-anneal | 13.1x14.7 | ” | 7

Life (hours) 500

Fig. 111
TENSILE TESTS AT 450°C ON FINNED TUBES OF SAP ISML 7% (ISML Results on various profiles Ref. 35 Batch N° 2007 to 3570)

Histograms of Maximum Tensile Stress ($S_u$) and plastic strain at breaking point (in black, results concerning the profile ISML9)

(whole bulk 192 specimens ISML9 93 specimens)

Mean value (whole bulk): 90 Kg/mm² Mean value (ISML9): 92 Kg/mm²

Number of specimens

Mean value (whole bulk): 3.2% Mean value (ISML9): 3.3%
TENSILE TESTS AT 450°C ON FINNED TUBES OF SAP ISML 7%.
Evolution of Mechanical Properties as a function of Batch Number
(ISML Results Ref 35 Batches No 2007 to 3091)

Su: Engineering maximum tensile stress
Specimen: L = 5 diameter
θρο: plastic strain at breaking point

Notes:
- ○: Su
- +θρο: plastic strain at breaking point

Graphical representation:
- Years of Production
- Batch No
- Specimen L = 5 diameter
- Su Kg/mm²
- θρο (%)

Years of Production:
- 1964
- 1965
- 1966
TENSILE TESTS AT 450°C ON FINNED TUBES (Profile ISML 9) OF SAP ISML 7%

Evolution of Mechanical Properties as a function of Batch Number (ISML Results Ref. 35 - Batch No 2459 to 3120)

Fig. 114

Su (Engineering maximum tensile stress)  \( \Theta \)

\( \Theta \)pb (Engineering plastic strain at breaking point)

Specimen: Lo = 5 x Diameter

<table>
<thead>
<tr>
<th>Batch No</th>
<th>1965</th>
<th>1966</th>
</tr>
</thead>
<tbody>
<tr>
<td>2400</td>
<td>2500</td>
<td>2600</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Su (Kg/mm^2)  \( \Theta \)

\( \Theta \)pb (%)
STRESS RUPTURE TESTS ON SAP ISML 4%
(Euratom and ISML Results)
Comparison between bars and tubes

<table>
<thead>
<tr>
<th>Type of Specimen</th>
<th>%Al2O3</th>
<th>Dimens mm</th>
<th>Batch No</th>
<th>Test Temp</th>
<th>Type of Stress</th>
<th>from Fig</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bars</td>
<td>4</td>
<td>9.5</td>
<td>289</td>
<td>460</td>
<td>Tension</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>SMOOTH TUBES</td>
<td>4</td>
<td>13.1 x 14.7</td>
<td>440-441</td>
<td>450</td>
<td>Internal Pressure (Tangential stress)</td>
<td>108</td>
<td></td>
</tr>
</tbody>
</table>

For tube specimens, C represents the tangential stress.
STRESS RUPTURE TESTS ON SAP ISML 7% (Euratom and ISML Results)

Comparison between bars and tubes

<table>
<thead>
<tr>
<th>%Al₂O₃</th>
<th>dims.</th>
<th>Batch No</th>
<th>Test temp</th>
<th>Type of stress</th>
<th>from Fig:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bars</td>
<td>7</td>
<td>9.5</td>
<td>275</td>
<td>Tension</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1722</td>
<td>Internal Pressure (tangential stress)</td>
<td>43</td>
</tr>
<tr>
<td>Smooth tubes</td>
<td>7</td>
<td>131x14.7</td>
<td>450</td>
<td>450</td>
<td>110</td>
</tr>
</tbody>
</table>

For tube specimens, \( \varepsilon \) represents the hoop stress (tangential stress).

![Graph showing stress rupture test results](image-url)
TENSILE TESTS AT 450°C ON BARS AND FINNED TUBES OF SAP ISML 7%

Comparison between finished product and base material

<table>
<thead>
<tr>
<th>%Al₂O₃</th>
<th>Dims. mm</th>
<th>Batch No</th>
<th>Report histogr Fig.</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar</td>
<td>7</td>
<td>Ø 21 x 16</td>
<td>from 1810 to 2623</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ø 14 x 15.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finned tubes</td>
<td>7</td>
<td>21 x 4 x 25</td>
<td>from 2007</td>
<td>112</td>
</tr>
</tbody>
</table>

![Graph showing tensile test results](image)

Mean value (tube) 9 Kg/mm²

Mean value (bar) 36 Kg/mm²

Mean value (tubes) 32%  Mean value (bars) 40%
Burst Tests on finned tubes of SAP ISML 7% at 460°C
Tangential stress at breaking point vs. depth of Defect.
(Euratom Results Ref. 62 bis)
FATIGUE BURST TESTS ON FINNED TUBES OF SAP ISML 7% UNDER INTERNAL PULSED GAS PRESSURE (Temperature 460°)
(Euratom Result Ref. 62 bis)

Su (Hoop stress) Kg/mm²

Symbols

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Depth of Defect (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>none</td>
</tr>
<tr>
<td>□</td>
<td>0.05</td>
</tr>
<tr>
<td>+</td>
<td>0.10</td>
</tr>
<tr>
<td>♦</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Number of cycles

Fig. 119
EXPERIMENTAL CONDITIONS
AND
COMPLEMENTARY RESULTS
3. EXPERIMENTAL CONDITIONS AND COMPLEMENTARY RESULTS

3.1 Mechanical Properties of Semi-finished products

3.1.1 Tensile Tests

3.1.1.1 Euratom and ISML Laboratory Tests

3.1.1.1.1 Test conditions

Test specimen

First of all, we can analyze the influence of the relation \( x = \frac{\text{length}}{\text{diameter}} \) as related to the specimen, on the elongation value on rupture on SAP ISML 10% for instance. Fig. 1 shows that the elongation decreases with increasing \( x \) because the influence of the elongation at necking diminishes with increasing length.

This effect is more clearly visible in Fig. 2, where the elongation values have been related to increasing values of \( \frac{1}{x} \).

Fig. 2 also shows the values of \( \frac{1}{x} \) for the specimens used by different laboratories (Section 2.1) which studied the SAP ISML, namely: Euratom, ISML, Risø (Ref. 41), AECL (Ref. 33), TLH (Ref. 67 to 86 Part II).

The drawings of the specimens used by Euratom and ISML are given in Figs. 3 and 4 respectively (dimensions in mm).
Testing instruments

In the Euratom laboratories we used a universal electric testing machine (Instron TTCM). The applied load is measured very accurately between 1 g and 5 t by means of a series of load cells, strain gauges being used as transducers. The crosshead speed can be varied very precisely within a range from 0.0005 to 50 cm/min. The influence of the tensile speed on the mechanical properties is presented on diagrams Nos. 6, 7, 8, 9, 9A, 9B, 9C.

In the ISML laboratories a hydraulic testing machine (Amsler) was used. The testing speed varies with the load and cannot be accurately determined. The measurement of the load is obtained directly from the variation of the pressure in the hydraulic system.

Measurement of elongation

In most of the current tests no extensometer was used except for very accurate measurements (as in Fig. 10).

In the ISML laboratories, which are primarily intended for fabrication control purposes, two marks are engraved on the specimen indicating the gauge length. After rupture the two parts are put together again and the new distance between the two engraved marks measured. For determination of Young's modulus extensometers of the Martens type are used.

In the Euratom laboratories the elongations are determined from the diagrams representing the load (P) as a function of the crosshead displacement (ΔL). This latter can be amplified over a wide range; generally, during the elastic part an enlargement of 100 x was used and during the rest of the test 10 x. If we consider the plastic elongation only, then the influence of the frame deflection of the machine is eliminated (Ref. 30).

For special measurements extensometers with inductive transducers or differential methods (specimens of different lengths) are employed.
Determination of the engineering yield stress

The engineering yield stress was always determined with the aid of the $P = f(ΔL)$ diagrams in continuous tests ($ΔL$ was enlarged 100 x). Afterwards a straight line at 0.2% plastic elongation was drawn parallel to the elastic line of proportionality (Ill. 5 & 6). Intermittent tests, causing a plastic elongation of 0.2% after unloading, were therefore not carried out. The diagrams in Fig. 10 give various values for the engineering yield stress, obtained by several methods at 20 and 450°C as a function of the percentage of Al$_2$O$_3$ and as a function of temperature for SAP 7%. The engineering yield stress at 0.004% is clearly lower than at 0.2% and is very near the limit of proportionality.

3.1.1.1.2 Results

Feature of the load elongation curves

In Illustration 6 are presented fac-simile of load-elongation curves obtained on the Instron recorder. We have chosen two representative tests (on SAP 7% at 20 and 450°C) in order to give an idea of the tensile behaviour of SAP material at room and at high temperature. Therefore, the two diagrams have been drawn at the same scale.

It can be seen on these curves that at high temperature, the difference between $S_{0.2}$ and $S_u$ is strongly reduced. At the same time, the uniform elongation ($e_{pu}$) decreases till nearly zero, so that the local necking initiates much earlier. In other words the zone of strain-hardening and the plastic reserve have practically disappeared.

Properties as a function of temperature for several grades of SAP

For each Al$_2$O$_3$ percentage a diagram of the tensile stresses ($S_{0.2}$ and $S_u$) and of the tensile strains ($e_{pu}$ and $e_{pb}$) is given as a function of the temperature (20 up to 600°C). Each point represents the average of at least three different tests.
LOAD-ELONGATION CURVES OF SAP ISML 7%

Definition of terms applied

TEST CONDITIONS
Specimen Fig 3
Crosshead speed: 0.2 cm/min
Magnification of elongations: 25

450°C Test

20°C Test
SAP ISML 4%

The properties were determined on two main batches: one old batch (fabrication of May 1961) and one more recent (fabrication of June 1962) Figs. 11 and 12. This latter batch has slightly better mechanical strength (10% at 20°C and 20% at 450°C) and lower elongation at 20°C.

SAP ISML 7% (Figs. 13 and 14)
SAP ISML 10% (Figs. 15 and 16)
SAP ISML 14% (Figs. 17 and 18)

Observation of the curves:

As a general rule, the tensile stresses and the elongation both decrease with increasing temperature. From about 300°C onwards $S_u$ mingles with $S_{0.2}$ and $e_{pu}$ reaches its minimum value which remains nearly constant up to 600°C.

Comparison of the four grades of SAP

For each property all four grades of SAP were compared (other presentation of previous results) on the following diagrams:

<table>
<thead>
<tr>
<th>Property</th>
<th>Fig. No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Euratom results</td>
</tr>
<tr>
<td>$S_u$</td>
<td>19</td>
</tr>
<tr>
<td>$S_{0.2}$</td>
<td>21</td>
</tr>
<tr>
<td>$e_{pu}$</td>
<td>23</td>
</tr>
<tr>
<td>$e_{pb}$</td>
<td>24</td>
</tr>
</tbody>
</table>

ISML gave averages for the results obtained from production control tests of extruded rods, over a three-year period. The curves are seen to behave similarly for each type of SAP.
Cumulative curves as a function of the percentage of Al₂O₃

- Diagrams of the tensile stresses (Fig. 26) and elongations (Fig. 27) for various temperatures between 20 and 600°C (values derived from the curves shown in Figs. 11 to 18); The tensile stresses increase with increasing oxide contents. However, the elongations decrease with increasing oxide percentages.

- Curves of the tensile stresses and elongations at 20 and 400°C determined by ISML on extruded rods (Fig. 28).

The latter curves were plotted with the aid of average values taken from the histograms (Figs. 86 and 87), representing three years of fabrication.

3.1.1.2 AECL Laboratory Tests (Ref. 33)

Test conditions

The tensile specimens (Fig. 31) were tested on a Hounsfield testing machine and the yield strength determined from the autographic record.

Test results

Only the values for SAP 4% are reported here. Tests have been carried out only at room temperature and above 375°C. The diagram of the stress versus temperature (Fig. 32) shows approximately the same values as Fig. 11. The diagram of the strain versus temperature (Fig. 33) lacks precision between 20 and 350°C but the general form of the 400-500°C range is the same as Fig. 12.

3.1.1.3 Risø Laboratory Tests (Ref. 41)

Test conditions

The tensile specimen has a diameter of 4.5 mm and a gauge length of about 45 mm. Either a 10 t Amsler or a 5 t Instron testing machine was used. With the latter (for more precise tests), a crosshead speed of 0.1 mm/min was applied up to S₀.2, the rest of
test being performed at 1 mm/min. The Amsler or Instron furnaces were regulated to within ± 3°C and the soaking time before testing was about 30 min. At least two specimens were tested for each temperature and SAP grade. The $S_{0.2}$ was always determined continuously with an extensometer.

Test results

Fig. 34 gives the properties at 20 and 400°C as a function of the percentage of Al$_2$O$_3$. Compared with the diagrams in Figs. 26 and 27 it will be seen that the tensile stresses agree with the classical values, but the strains are slightly lower, especially at 400°C.

3.1.2 Compression Tests (Euratom results)

3.1.2.1 Experimental Conditions

Shape of the test specimen

We chose the same diameter (4 mm) as for the cylindrical part of the tensile specimen (Fig. 3). After having studied the compression behaviour of specimens from various heights (three times, twice, once the diameter) a cylinder with a height equal to its diameter was taken as a specimen (thus minimizing the effects of parasitic buckling).

Testing machine

For the compression test we used an Instron TTM universal electrical testing machine. The velocity of the crosshead (1 mm/min) was enlarged a hundred times on the load-elongation diagram.

3.1.2.2 Behaviour of the "Engineering Stress-Strain" Diagrams

Construction of the curves (Illustration 5, section "Symbols"

As for the tensile test, we used the "load-elongation" diagrams plotted by the machine. The section of which the tensile stress can be calculated is the original section of the specimen. The strain is calculated on the basis of the original height of the specimen before the test.
Observation of the curves

Ill. 5 shows the behaviour of the diagrams for a tensile test and for a compression test. The symbols used for compression are the same as those for tensile tests (see Table 2), but followed by an apostrophe.

In the elastic region the inclination angles $\alpha$ and $\alpha'$ of the curves are different, since the deflection of the machine is not the same. This difference is eliminated by considering only the plastic strains. The maximum engineering tensile stress ($S'_u$) is assumed to be the stress which corresponds to point B' where the curve shows a point of inflection, this latter also enabling the value of elongation $e'_p$ to be calculated. This is logical, whereas in a "true stress/true strain" diagram the tensile and compression curves show the same behaviour, since in that case the point B is also a point of inflection.

3.1.2.3 Results: Cumulative curves for tensile and compression stresses and elongations as a function of the temperature for the four grades of SAP ISML

<table>
<thead>
<tr>
<th>Properties</th>
<th>Results of tensile tests in Fig.</th>
<th>Results of compression tests in Fig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S'_u$</td>
<td>19</td>
<td>35</td>
</tr>
<tr>
<td>$S'_0.2$</td>
<td>21</td>
<td>36</td>
</tr>
<tr>
<td>$e'_p$</td>
<td>23</td>
<td>37</td>
</tr>
<tr>
<td>$e'_p$</td>
<td>24</td>
<td>--</td>
</tr>
</tbody>
</table>

The engineering 0.2 offset yield stress ($S'_0.2$, Fig. 36) under compression is slightly higher than $S_{0.2}$ under tensile stress, especially at 20°C. The maximum engineering compression stress ($S'_u$, Fig. 35) at 20°C is higher than $S_u$ (about 30%), but at higher temperatures becomes comparable.
The engineering plastic uniform strains \( (e'_p) \) in compression tests are clearly higher than the \( e_p \)-values under tensile stress. The minimum values - which were situated around 300°C for \( e_p \) - are shifted to about 450°C for \( e'_p \). Thus this behaviour of \( e'_p \) looks like that of \( e_p \) under tensile stress (Fig. 23).

In conclusion it may be said that both the tensile and the compression test results show a drop in stress and strain for increasing temperature.

3.1.3 Creep Tests

3.1.3.1 Euratom-ISML Tests

3.1.3.1.1 Test conditions:

- **Test specimens:**
  The test specimens used by the Euratom and ISML laboratories are given in Figs. 38 and 39 respectively. The former were taken from rods with a diameter of 9.5 mm, and the latter from rods with a diameter of 21 mm.

- **Testing machines:**
  Euratom tests:
  We used Adamel TAC stress-to-rupture machines fitted with a modified electrical accessory permitting magnifications up to 500 times (this magnification value has always been used for tests on SAP because of the low elongation values of this material). The extensometer is fixed above the heads of the test specimens, i.e., at the two ends. The temperature is controlled by two Chromel Alumel thermocouples, and regulation of the furnace keeps the temperature constant to ± 1.5°C.

ISML tests:
  The tests quoted in this report were carried out in the laboratories of AIAG/Neuhausen. The extensometer was fixed in two grooves in the heads of the test specimen (Fig. 39). The temperature of the test specimen was maintained at ± 1°C.
3.1.3.1.2 Stress-to-rupture curves

The ISML tests were performed at 400°C and the Euratom tests at 420 and 460°C. The stress-to-rupture tests were drafted in semi-logarithmic scales up to 10,000 hr. Each of these curves shows a sudden change in the slope at a point which varies with each percentage of Al₂O₃. The test specimens show no tertiary creep, and no re-acceleration of the elongation just before rupture of the specimen.

**SAP 4%**: Fig. 40
**SAP 7%**: Fig. 41: Results for an old batch (made in May 1961). The results at 460°C show a slight scatter.

**Fig. 42**: Stress-to-rupture at 420°C. For the same batch as before, the scatter is lower.

**Fig. 43**: These results refer to more recent batches (1964 and 1966) and show very marked scatter; around a stress of 5 kg/mm² the scatter amounts to 0.35 kg, i.e., 7%.

**Fig. 44**: Uniform elongations. These values were obtained with the aid of the tests described in Fig. 43 and are tabulated in a histogram. The elongations at loading are of the order of 0.5%. At rupture, the average elongation is of the order of 0.8% and the minimum elongation 0.4%.

**SAP 10%**: Fig. 45
**SAP 14%**: Fig. 46

3.1.3.1.3 Cumulative diagrams

The previous results were tabulated in cumulative diagrams as a function of various parameters.

**Stress-to-rupture curves**

- Stress-to-rupture of SAP 7% at 400, 420 and 460°C (Fig. 47). The relative position of the curve obtained at 420°C as compared with those at 400 and 460°C does not seem to be very logical when an attempt is made to interpolate linearly for an intermediate temperature.
- Stress-to-rupture at 400°C for the four oxide percentages (ISML results) (Fig. 48). The changing point of the slope for each curve varies somewhat from one oxide percentage to another. The relative curve at 7% seems to be abnormally displaced upwards.

- Stress-to-rupture at 460°C for the four percentages of oxide (Euratom results) (Fig. 49). The curves show rather similar slopes.

Stress to produce creep strain of 0.1% at 400°C (ISML results, Fig. 50)

Because there is considerable scatter of the results of the elongation measurements (see histogram in Fig. 44), this curve can only be regarded as a tendency.

Elongation curves at 400°C for 1,000 hr as a function of the applied stress (ISML results, Fig. 51)

The values given are very low, but the number of observations is very small, so these curves are merely regarded as indicative.

3.1.3.2 Battelle Institute Tests (Frankfurt)

Test conditions

Test specimens (Fig. 54): taken from rods 21 mm in diameter

- Testing machine:

The machines used were designed at the Institute. The knives of the extensometer are fixed to the heads (the two ends) of the test specimen. The elongation was measured with the aid of a microscope. The light-beam passed through a quartz window mounted in the wall of the furnace. The absolute accuracy of the measurement is to within about 3 microns. The temperature of the test specimen is kept constant to ± 3°C.

Stress-to-rupture curves for SAP 4% and 7% at 460°C

Stress-to-rupture curves (Fig. 55):

The results refer to two batches (batch 645 of March 1962 and batch 890 of October 1962). For a given stress-to-rupture time,
the scatter of the stress values is of the order of 12%. The values obtained for the more recent batch seem to be lower.

**Elongations (Fig. 56):**
The results are so scattered that we preferred to present them in the form of histograms.

Minimum elongation at rupture 0.2 to 0.3%.
Average elongation about 0.45%

**SAP 7%:** The study refers to three batches (December 1961, October 1962, September 1963). Stress-to-rupture (Fig. 57):
The more recent batches seem to be less resistant, especially for long duration.

Elongations (histogram in Fig. 58):
Minimum elongation at rupture 0.2 to 0.3%
Average elongation about 0.5%

These elongations are comparable to those obtained for SAP ISML 4%:
The elongation scatter has dropped in comparison with that in the Euratom results (Fig. 44) and the mean value of the Battelle data is lower (0.5 as opposed to 0.8%).

3.1.3.3 **AECL Tests**

**Test specimen (Fig. 59)**

Stress-to-rupture curves of SAP ISML 4, 7 and 10% at 426°C (800°F) (Fig. 60)
The results obtained by AECL at 426°C are as low as those obtained by Euratom at 460°C (see Fig. 49). As far as SAP ISML 7% is concerned, these results are 15% less than those obtained by Euratom at 420°C (Fig. 47).

3.1.3.4 **Comparison of Results Obtained by Battelle Institute and Euratom**
These two laboratories in fact carried out similar tests on SAP ISML 4% and 7% at 460°C. However, the diameter of the rods from
which the test specimen were taken and therefore the extrusion ratio were different, as indicated below:

<table>
<thead>
<tr>
<th>diameter of rods (mm)</th>
<th>extrusion ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>rods used by Euratom</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>74</td>
</tr>
<tr>
<td>rods used by Battelle Institute</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>15</td>
</tr>
</tbody>
</table>

The stress-to-rupture curves given previously are compared in one diagram (Fig. 61)

SAP 4²

The Euratom results are situated in the lower part of the scatter range of the Battelle findings.

SAP 7²

The overlapping areas of the results obtained by the two laboratories refer to older batches (No. 551 and 906). The lower values refer to a more recent batch (No. 1300).

3.1.4 Relaxation Tests

3.1.4.1 Test Conditions

Test specimen

Test specimen TR 1 (Fig. 3) 
Test specimen of 7 mm diameter (Fig. 63) 
Test specimen ISML (Fig. 62) 

Euratom laboratories

Testing machines

Electronic relaxation machine (Euratom) (Ref. 62)

This machine was developed by Euratom under contract. The test specimen, which is placed in a closed room under vacuum, is fitted with two extensometer shafts connected to a transducer of capacitive displacement. A dynamometer, also connected to a
capacitive transducer, is inserted in the loading system under vacuum. The bridges intended for measuring the load and elongation form a system which is closed in such a way that it is possible to work at constant load (creep test) or at constant elongation (relaxation test), thus eliminating the inherent deformations of the machine frame and the friction forces at the passages into the vacuum chamber. The upper part of the enclosure in which the test specimen is situated is placed in a furnace the temperature of which may be regulated to ± 1.5°C.

**Machine for creep test** (Adamel TR-3 Euratom) (Ref. 57)

With this apparatus the isothermal viscosity can be tested up to 60 kg/mm² and the stress relaxation up to 40 kg/mm² on a test specimen 4 mm in diameter. The test specimen is put into a furnace (temperature ± 1°C). The load is applied with the aid of a lever and a spring. The extremities of the two quartz shafts of the extensometer are held in two holes drilled in the axis at the ends of the heads of the specimens. The displacement of the extensometer shafts is mechanically magnified up to 1000 times. The extensometer actuates an electrical contact which starts a motor to change the loading spring.

**Relaxation machine of the ISML laboratory** (Ref. 21) (Baldwin modified)

Essentially the machine consists of an extensometer which is fixed to the test specimen and sends out the signal for regularization of the load. The variations in the load in time are directly recorded by the machine. The furnace for heating the test specimen is provided with a special regulating system by which the temperature can be kept constant at less than 1°C.

**Universal testing machine Instron type TTCM** (Euratom Ref. 60)

The first orientation tests carried out by Euratom were made on this machine, according to a method described by the designer (Ref. 61). Essentially it consists in applying a certain load after which the movable crosshead is held rigid and the decrease
in the load as a function of the time is accurately measured. The application of this method is rather tricky because the deflection of the machine frame and the temperature variations have to be taken into consideration.

A correction factor for the machine deflection could be established approximately from a short test series in the following way. An extensometer was used (magnification 1000 x and an error of less than 1%); after the desired initial load had been applied, the position of the crosshead was corrected manually in order to maintain the initial elongation of the specimen.

The decrease in the load as a function of the time thus measured was three times as high as the values found earlier by the simpler method. We therefore applied this correction factor, equal to 3, in the following results.

5.1.4.2 Euratom Results

We principally studied the SAP ISML 7% and performed three series of tests, applying initial stresses equal to 1/3, 2/3 and 3/3 of the yield point at 0.2% (\(S_{0.2}\)).

at 20°C (Refs. 58-60, Fig. 64)

The preliminary results give an idea of the behaviour of the curves. The decrease in the stress expressed as a percentage of the initial stress is indicated in the table below:

<table>
<thead>
<tr>
<th>Initial stress</th>
<th>1 hr</th>
<th>5 hr</th>
<th>10 hr</th>
<th>100 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1/3 S_{0.2})</td>
<td>3</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(2/3 S_{0.2})</td>
<td>5</td>
<td>9</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>(3/3 S_{0.2})</td>
<td>18</td>
<td>23</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

at 450°C (Refs. 57, 58 and 60, Fig. 65)

For stresses equal to 2/3 of the yield point, the curves show a change in slope which is especially visible in the region of 1 hr.
For lower stresses, the slope of the curve is less. The slopes of the curves obtained with three different machines are very comparable. The decrease in the stresses is reported in the table below:

In Fig. 65a only the relaxation curves obtained with the Instron machine are shown. They correspond to initial stresses of 1/3, 2/3 and 3/3 of $S_{0.2}$ at 450°C. The higher the stress, the steeper the slope.

<table>
<thead>
<tr>
<th>Initial stress</th>
<th>Decrease in the stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 hr</td>
</tr>
<tr>
<td>1/3 $S_{0.2}$</td>
<td>16</td>
</tr>
<tr>
<td>2/3 $S_{0.2}$</td>
<td>20</td>
</tr>
<tr>
<td>3/3 $S_{0.2}$</td>
<td></td>
</tr>
</tbody>
</table>

3.1.4.3 ISML Results (Ref. 21, Fig. 66)

The partial results given here are for SAP 7%. Preliminary creep tests have shown that the deformation imposed at the beginning of the test should not subject the material to stresses in excess of 5 kg/mm² (i.e., 2/3 of the yield point). The first test specimen underwent a deformation of 0.165%.

The decrease in the stress is reported in the table below:

<table>
<thead>
<tr>
<th>Initial stress</th>
<th>Decrease in the stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 hr</td>
</tr>
<tr>
<td>0.55 $S_{0.2}$</td>
<td>25</td>
</tr>
</tbody>
</table>

The behaviour of the curve is very different from that obtained on the various machines used by Euratom. The phenomenon seems to slow down after 10 hr, whereas in the other cases it speeds up.
3.1.5 Impact Strength Tests (Refs. 9 and 10)

3.1.5.1 Test Conditions

The standard Charpy specimen was used (Fig. 67). The specimen was machined from bar stock 10.3 x 10.3 mm square (E = 60) and afterwards annealed for two hours at 500°C. The instrument used was an Amsler machine; the hammer energy applied was 30 mkg. With the same hammer lower energies were applied, as indicated in Fig. 68. For the high-temperature tests every specimen was soaked at its testing temperature for 30 min. Generally five tests were performed for each temperature.

3.1.5.2 Results

The impact strength of SAP ISML 4% and 7% Al2O3 versus temperature is shown in Fig. 68. It is clear that the impact strength increases with temperature. The part of the curve shown as a dotted line indicates values which are too low because at these points the specimens did not rupture completely.

The curve for SAP 7% lies below the 4% Al2O3 curve, thus indicating a lower ductility, which is in agreement with other types of mechanical tests. There are two individual points (at 20 and 400°C) for SAP 4% which are well below the established SAP 4% curve. These points were obtained for a very old batch made under quite different fabrication conditions (only simple extrusion was applied).

3.1.6 Hardness Tests

3.1.6.1 Macrohardness

Brinell Macrohardness: ISKL (Ref. 2-4) measured the Brinell macrohardness at 20°C applying a ball diameter of 2.5 mm, a load of 62.5 kg and a time of 30 sec. Results as a function of oxide contents are given on Fig. 70.

The same laboratory performed tests up to 400°C on SAP 7 and 14% (Ref. 21b). The test conditions were as follows: ball diameter 5 mm, load 125 kg maintained during 3 min. Results are given on Fig. 70b.
Similar tests have been done in Euratom laboratories up to 600°C with a machine of Euratom construction. The test conditions were as follows:

- ball diameter: 2.5 mm
- loading speed: 0.4 mm/s
- load maintained during 3 mins.
- number of indentations for each temperature: 4
- maximum difference of temperature between two indentations: ± 3°C.

Results are reported on Fig. 70 a

**Vickers Macrohardness**: Euratom measured the Macrohardness with a Tukon-Wilson tester by the Vickers method. A load of 1 or 2 kg was used as can be seen in Fig. 69. Five different samples were prepared for each SAP grade and three separate indentations were made on each sample.

3.1.6.2 **Vickers Microhardness** (Euratom results)

Euratom measured the microhardness at room temperature with a Leitz-Durimet by the Vickers method (load 100 g, time 10 s). The arithmetic mean of ten measurements for each grade of SAP is reported in Fig. 69.

Preliminary results of Vickers Microhardness at high temperature have also been obtained in the Euratom laboratories with a new machine developed under contract (S.E.A.V.O.M./EURATOM)(Ref. 28bis). The maximum difference of temperature between two successive indentations on the same specimen is reported on the table below:

<table>
<thead>
<tr>
<th>Test temperature (°C)</th>
<th>Maximum temperature difference ±</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000</td>
<td>8</td>
</tr>
<tr>
<td>600</td>
<td>4</td>
</tr>
<tr>
<td>400</td>
<td>2</td>
</tr>
</tbody>
</table>

The indenters are made of diamond. The heating of test specimen is obtained through electron bombardment, the vacuum of the cham-
ber being maintained between $10^{-5}$ and $10^{-6}$ Torr.

The test conditions were as follows:
- load: 50 g
- loading duration: 1s
- load maintained during 20 s
- number of indentations for each temperature: 3 to 4
- number of measurements possible on one specimen: >100
- the measurement of indentation is made at the required temperature

The results are given on Fig. 69A.

3.1.7 Fatigue Tests by Rotating Bending (ISML results)

3.1.7.1 Fatigue Life at 20°C and 400°C

Test conditions (Ref. 8)

The fatigue test specimen for this series of tests is shown in Fig. 74. The surface finish was held between 0.09 and 0.1 micron and was measured by a Taylor-Hobson roughness meter in the longitudinal direction of the specimen. The rotating bending fatigue machine was a Schenck-Duplex, turning at 3,000 rpm.

Results

The results are shown in Figs. 75-79 for 20 and 400°C. Generally speaking, the 400°C curve is about 50% lower than the 20°C curve. The maximum number of cycles was $10^8$, but the curves did not reach the asymptotic value at this point, so the real fatigue limit is not known. Thus we can only speak of a fatigue life at $10^8$ cycles.

From the same batch some tensile tests were carried out in order to compare the results of the two tests.

<table>
<thead>
<tr>
<th>Ratio [ \frac{F}{S_{0.2}} ]</th>
<th>( % \text{Al}_2\text{O}_3 )</th>
<th>4</th>
<th>7</th>
<th>10</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>at 20°C</td>
<td>0.56</td>
<td>0.48</td>
<td>0.49</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>at 400°C</td>
<td>0.92</td>
<td>0.71</td>
<td>0.68</td>
<td>0.60</td>
<td></td>
</tr>
</tbody>
</table>
In the above table the ratio between the fatigue life at $10^3$ cycles ($F$) and the 0.2 offset yield stress is given for four SAP grades at 20 and 400°C.

5.1.7.2 Notch Effect in Fatigue Tests by Rotating Bending at 20°C

Test conditions (Ref. 2)

The unnotched specimen is shown in Fig. 81 and the notched one in Fig. 80. The details of the V- and U-notch are also visible in Fig. 80. The surface finish was held between 0.09 and 0.1 micron, as above. The apparatus was an ISML FRS type turning at 11,500 rpm.

Results

The results are given in Figs. 82-85. Each graph shows the unnotched and notched (U-form) fatigue results up to $10^8$ cycles for a given SAP alloy (4, 7, 10 or 14% $\text{Al}_2\text{O}_3$).

<table>
<thead>
<tr>
<th>$%\text{Al}_2\text{O}_3$</th>
<th>4</th>
<th>7</th>
<th>10</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_n/F$</td>
<td>0.42</td>
<td>0.48</td>
<td>0.45</td>
<td>0.55</td>
</tr>
</tbody>
</table>

The ratio of the fatigue life ($F_n$) up to $10^8$ cycles for the notched (U-form) and unnotched specimen ($F$) is given above. Generally speaking, the notch effect is less severe with increasing $\text{Al}_2\text{O}_3$ contents. Besides the U-notch (Neuber coefficient = 2.2), a V-notch (Neuber coefficient = 9) was applied in two test series on SAP 4% and 7%.

From Figs. 82 and 83 it can be seen that the form of the notch has no major influence, except for low cycle values of the SAP 4%.

With different conditions, as in Section 3.1.7.1, we can again determine the ratio $F/S_{0.2}$ at 20°C for the unnotched specimen.

<table>
<thead>
<tr>
<th>$%\text{Al}_2\text{O}_3$</th>
<th>4</th>
<th>7</th>
<th>10</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_n/S_{0.2}$</td>
<td>0.60</td>
<td>0.50</td>
<td>0.55</td>
<td>0.45</td>
</tr>
</tbody>
</table>
The ratio between the fatigue life ($F_n$) at $10^8$ cycles and the 0.2 offset tensile yield stress is given in the above table. The same tendency is visible as in Section 3.1.7.1, that is to say, the reduction in the strain (difference $S_{0.2} - F_n$) is more severe for a high percentage of $\text{Al}_2\text{O}_3$.

3.1.8 Gradual Evolution of Batch Quality (ISML Results)

3.1.8.1 Scatter of Results (Refs. 11 and 35)

Histograms of the tensile properties ($S_{0.2} - S_u - e_{pb}$) of different grades of SAP are given in Figs. 86-87-88. They originate from:

- a) production controls of the standardized production
- b) controls of major changes in the standardized production method
- c) verification of batches destined for special laboratory test series (e.g., impact strength, creep, fatigue, hardness, etc.).

In Figs. 86 and 87, which give the results for 20 and 400°C, the data are not complete because the numbers in the ordinates of the histograms are not listed. Furthermore, the results in Figs. 86 and 87 are for very old batches produced before the end of 1962.

The more recent results on complete histograms are given in Fig. 88, which contains 43 test results for SAP 7% at 450°C.

These 43 tensile tests were selected from batches which were fabricated under standard conditions. For the histograms of Fig. 88 the scatter can be roughly defined as:

- for the stresses $\frac{8.1 - 6.8}{7.57} = 17\%$
- for the strains $\frac{6 - 2.5}{4.38} = 80\%$
3.1.8.2 Properties as a Function of Batch Number (Ref. 35)

Figs. 89-91 showed the curves of the mechanical properties ($S_{0.2} - S_u - e_{pb}$).

The tensile test results were selected in order to represent only batches made under standard fabrication conditions.

The method of manufacturing the base material (the starting powder) was unchanged until the end of 1962 (batch No. 1,000). Furthermore, the tensile testing temperature was changed from 400 to 450°C.

The three diagrams give an idea of the evolution. There is instantaneous scatter - in the vertical sense, as for batch numbers which are close to one another - and long-term scatter - in the horizontal sense, as with the time axis. These two types of scatter are difficult to express in figures owing to the lack of results.

The existence of this "scatter range" also has an effect on the 85 preceding diagrams. These are results relating to a certain batch number and thus these data are not representative for SAP as a whole.

If the results of the previous 85 diagrams are to be used, it will be necessary to apply a safety margin, which is related to the width of the "scatter range".

3.2 Influence of the Mechanical and Thermal Treatments on the Extruded Product.

The extruded product is only the base material for the preparation of the finished products. It has already been stated (Section 1.7) that in certain cases (thin-walled tubes, plates, foils) it is necessary to use cold-deformation (rolling or cold-drawing). The evolution of the mechanical properties after cold-deformation as compared with the properties of the extruded product was therefore studied. Furthermore, it is nearly always necessary to in-
clude an annealing treatment and often the operating temperature of the final product is quite high, so the evolution of the properties of the material as a function of the annealing temperature was examined.

The main results obtained are given here and the reader is referred to the specific paragraphs of each type of test for details of the general experimental conditions.

3.2.1 Influence of Cold-Deformation

3.2.1.1 Tensile Tests (Refs. 27 and 46, Figs. 28 and 29)

The study was carried out on SAP ISML 4% extruded (E = 2.5) and then rolled (H = 92%). At room temperature the rupture strength of the rolled product (Fig. 28) is higher than that of the extruded material. At 20°C, as expected, the plastic strain (Fig. 29) is lower after cold-deformation. The high-temperature tensile tests (heating time + time at temperature 1 hour, so annealing effect cannot be avoided) demonstrate lower strength and higher ductility in the 300-500°C range for the cold-deformed samples. Near 600°C, however, the differences become negligible.

3.2.1.2 Vickers hardness tests (Ref. 56)

The Vickers hardness versus the degree of deformation for aluminium and the four SAP ISML alloys is plotted in Fig. 71. For the same degree of deformation the absolute increase in the Vickers hardness rises with the Al₂O₃ content.

3.2.2 Influence of Heat Treatment After Rolling

3.2.2.1 Tensile Test (Refs. 27 and 46, Figs. 28 and 29)

The tests were performed on SAP ISML 4% only. With a treatment of 3 hr at 620°C an attempt was made to recrystallize the rolled material, or at least to recover it.

In diagrams (Figs. 28 and 29) this recrystallization effect is clearly noted for tensile tests at 20°C, that is to say, for increasing ductility and decreasing strength values.
Some strange phenomenon occurs at 300 and 400°C. At 300°C, the ductility of the recrystallized material has the same ductility values as the extruded material. At 400°C the strength of the recrystallized material lies between the rolled and the extruded strengths.

3.2.2.2 Vickers Hardness (Ref. 56)

In Fig. 72 the recovery of Vickers hardness from $H_v$ 75 to $H_v$ 52 is plotted versus the annealing temperature for SAP ISML 4%. All the specimens were annealed together for one hour at the temperatures given in the figures. The specimens were alternately heat-treated, then measured, etc., right through the whole temperature range from 20 to 660°C. This figure shows that for an alloy which has undergone only 22% deformation complete recovery is obtained only at extremely high annealing temperatures. With increasing deformation, the recovery temperature is shifted to a slightly lower temperature. Fig. 73 shows the change in the recovery temperature of different alloys for a deformation of 95%. A shift in the recovery temperature to higher values for increasing Al$_2$O$_3$ contents is clearly visible. In conclusion, it may be said that the SAP structure is stable, recovery and in particular recrystallization being obtained only by thermomechanical treatment which lay completely outside the field of industrial practice.

3.2.3 Influence of the Heat Treatment on SAP 4% at 460°C (Ref. 46)

Creep tests were carried out on test specimens which were taken from the same batch and had undergone heat treatment at extremely high temperature (540°C; melting point of Al = 660°C) for periods of between several hours and 3,000 hr. The results are given in Fig. 52. It can be seen that treatment at high temperature of very long duration considerably lowers the properties of the material.

3.2.4 Influence of Thermal Cycling During Creep Test (Ref. 49, Fig. 55)

Thermal cycling of the specimen was effected in the course of a creep test at 460°C by switching off the heating furnace four times in 24 hr until the temperature reached 340°C. No influence on the stress-to-rupture curve was observed.
3.2.5 Influence of previous creep test on tensile properties

3.2.5.1 Euratom results

In order to see if the elongation of the specimen in creep test (at 460°C) does reduce the amount of elongation obtainable in tensile tests (at 450°C) we performed tensile tests on specimens which had remained unbroken after creep tests at a stress level of 0.6 $S_u$. The test conditions, both for creep and tensile tests were the standard ones (see Sections 3.1.1.1 and 3.1.3.1) but naturally the creep specimen (Fig. 38) was also used for tensile tests.

Tests have been done on an old Batch (No. 275) and a more recent one (No. 1720-1722). The final results are given on the table below.

Evolution of tensile properties after creep of SAP ISML 7% related to tensile properties without previous creep

<table>
<thead>
<tr>
<th>Material: SAP 7%</th>
<th>Evolution of tensile properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta S_{0.2}$ (kg/mm$^2$)</td>
</tr>
<tr>
<td>Batch No.</td>
<td>Origin of powder</td>
</tr>
<tr>
<td>275</td>
<td>AIAG</td>
</tr>
<tr>
<td>1720 1722</td>
<td>Eckart-Werke</td>
</tr>
</tbody>
</table>

The behaviour of the two batches are opposite in strength. However for both batches, the elongation shows a tremendous decrease.

3.2.5.2 ISML results (Ref. 14)

Tests have been done at 400°C on old batches of SAP ISML 4, 10 and 14%. The test specimens (Fig. 39) machined from bars Ø 21 mm have been submitted to creep tests up to 5,000 hours at a stress level of 0.66 $S_u$, without rupture. Tensile specimens (Fig. 4)
were machined out of creep specimens and then tested. As for Euratom results, we give on the table below the evolution of tensile properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Evolution of tensile properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batch No.</td>
</tr>
<tr>
<td></td>
<td>381</td>
</tr>
<tr>
<td></td>
<td>409</td>
</tr>
<tr>
<td></td>
<td>416</td>
</tr>
</tbody>
</table>

As a comparison basis, we have chosen the values of tensile properties obtained on bars Ø 16 mm according to Fig. 27. We had previously shown (Fig. 24) that there was no large increase in the values of $e_{pb}$ from a bar Ø 16 and a bar Ø 21 mm.

We see that the decrease of elongation is in good agreement with Euratom conclusions.

3.3. Mechanical properties of finished products

3.3.1 Smooth Tubes

3.3.1.1 Tensile Tests (ISML Results, Ref. 22)

Figs. 105 to 107 contain some tensile properties ($S_{0.2} - S_u - e_{pb}$) as a function of the percentage of $\text{Al}_2\text{O}_3$ for:

- simple extruded smooth tubes (position 2)
- extruded smooth tubes, afterwards cold-drawn (position 3)

Other test conditions are not known.

As was already known in the case of bar material, it will be seen that an increase in the $\text{Al}_2\text{O}_3$ content is accompanied by increasing stress and decreasing strain. If we compare positions 2 and 3 in Figs. 105, 107 and 108, the influence of the cold deformation can clearly be seen:
at 20°C higher stresses and lower strains
- at 450°C lower stresses (especially for SAF 10%) and no significant differences in strain.

3.3.1.2 Burst Tests (Euratom Results)

The tubes were tested in a furnace at 460°C under internal gas-pressure (Nitrogen) up to rupture. The test specimens were 300 mm long and a thermocouple was set inside the test specimen. They were closed by two plugs consisting of an internal aluminium ring pressed on to the tube wall by two cones. The rate of pressure increase was about 10 kg/cm² per minute, so the test duration was comprised between 4 and 7 minutes.

The smooth tubes were extruded and then cold-drawn but not annealed. They were left in furnace 1½ hours for temperature equilibration. The resulting transverse stresses (hoop-stress) (in kg/mm²) are listed in the following table.

<table>
<thead>
<tr>
<th>Test specimen</th>
<th>% Al₂O₃</th>
<th>4</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch No.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production early 1962</td>
<td>2265 to 2273</td>
<td></td>
<td></td>
</tr>
<tr>
<td>diameters (mm)</td>
<td>13.1</td>
<td>14.7</td>
<td>25.5</td>
</tr>
<tr>
<td>Test conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration (min)</td>
<td>7</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Number of tests</td>
<td>5</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>4.3</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>4.0</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>3.5</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>Scatter %</td>
<td>20%</td>
<td>35%</td>
<td></td>
</tr>
</tbody>
</table>
Referring to tensile tests on smooth tubes (Fig. 105), we find:

\[
\begin{align*}
\text{SAP 4}\% & \quad S_u = 5 \text{ kg/mm}^2 \\
\text{SAP 7}\% & \quad S_u = 6.3 \text{ kg/mm}^2
\end{align*}
\]

so the ratio for transverse stress \((S_{tr})\) and longitudinal stress \((S_{lo})\) becomes

\[
\begin{align*}
\text{for SAP 4}\% & \quad S_{lo} / S_{tr} = \frac{5.2}{4.0} = 1.25 \\
\text{for SAP 7}\% & \quad S_{lo} / S_{tr} = \frac{6.3}{5.2} = 1.2
\end{align*}
\]

However, the thermal treatment applied to burst test specimens and to tensile test specimens are not the same, so, the difference in transversal and longitudinal rupture stresses would be somewhat higher.

3.3.1.3 Stress-rupture Tests Under Internal Gas Pressure
(Euratom and ISML results) Refs. 8 and 52.

Both laboratories used the same principle as described above in Section 3.3.1.2, but for these creep tests it was necessary to maintain a certain constant gas pressure and to record the time-to-rupture.

Stress rupture curves up to 100 hours are given for SAP 4\% and 7\% and 400 and 450°C in Figs. 108 and 110. The influence of the temperature and \(\text{Al}_2\text{O}_3\) percentage are quite normal. A more complete curve up to about 1,500 hours based on two different batches of SAP 4\% is given in Fig. 109.

A comparison between two different laboratories (and different batches) is made in Fig. 115. The Euratom results at 100 hours are about 25\% lower than those of ISML.

The creep properties of three different production processes are compared in Fig. 111. The creep properties of the extruded tube are largely superior to the tubes which are afterwards cold-drawn and the stresses drop again when the tubes are annealed afterwards (maximum difference about 50\%).
3.3.2 Finned Tubes

ISML fabricated different types of finned tubes necessary for the different solutions of neutron - and heat-transfer - calculations. The general features of the tube profiles are given in the table below.

<table>
<thead>
<tr>
<th>Profile number Description</th>
<th>3</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of thermal fins</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>32</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>28</td>
</tr>
<tr>
<td>No. of spacers</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>type of fins straight S</td>
<td>H</td>
<td>H</td>
<td>S</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>S</td>
<td>H</td>
</tr>
<tr>
<td>helical H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>internal diameter (mm)</td>
<td>25.5</td>
<td>25.5</td>
<td>25.5</td>
<td>21.15</td>
<td>25.4</td>
<td>24.9</td>
<td>24.9</td>
<td>14.6</td>
</tr>
<tr>
<td>wall-thickness (mm)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>tolerances + 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>external diameter of</td>
<td>29.9</td>
<td>29.5</td>
<td>29.5</td>
<td>24.95</td>
<td>29.8</td>
<td>28.9</td>
<td>28.9</td>
<td>18.4</td>
</tr>
<tr>
<td>thermal fins</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>external diameter of</td>
<td>33.5</td>
<td>30.5</td>
<td>30.5</td>
<td>27.55</td>
<td>32.1</td>
<td>29.9</td>
<td>29.9</td>
<td>-</td>
</tr>
<tr>
<td>spacers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3.2.1 Tensile Tests

Many tensile tests were performed for production control purposes. Two properties ($S_u$ and $e_{pb}$) are shown in histograms in Fig. 112 in order to give an idea of the scatter. Two types of histograms are superimposed, one for the results for all the tubes, and the other for profile No. 9. As usual, the elongations are measured after rupture by putting the two parts of the tube together. The new distance between two marks is then determined. However, from this value must be subtracted the maximum clearance which remains when the two halves are put together.

The arithmetical mean values of profile No. 9 are about 2½ higher than the values for all the tubes, so this single profile seems to be really representative of the whole bulk.
Comparison between extruded finned tubes and smooth tubes shows good agreement.

<table>
<thead>
<tr>
<th>Properties at 450°C for 7½ SAP types of specimen</th>
<th>( S_u (\text{kg/mm}^2) )</th>
<th>( e'_{pb} (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>smooth tubes (annealed 2 hr/500°C: Fig. 105 Ref. 22-31)</td>
<td>8.6</td>
<td>2.5 to 3.7</td>
</tr>
<tr>
<td>finned tubes (non-annealed)</td>
<td>8.9</td>
<td>2.9</td>
</tr>
<tr>
<td>finned tubes profile No. 9 (non-annealed) Fig. 112, Ref. 35</td>
<td>9.2</td>
<td>3.3</td>
</tr>
</tbody>
</table>

3.3.2.2 Compression tests

Experimental conditions

As for cylindrical specimens, an Instron TCMLE testing machine was used and the tests carried out at 450°C. The test specimens consisted of pieces of tube carefully cut perpendicular to their axis. Their length was approximately equal to the greater external diameter of the tube.

Results

The rupture stresses are the ratio of the rupture load and of the cross-area (S) of the tube. The "maximum engineering stress", the "engineering 0.2 offset yield stress" and the "plastic uniform strain" are defined as for cylindrical specimens (see Illustration 5). Here, the values of \( e'_{pb} \) have no sense, because the breaking point is not reached, as it is in tension tests. The main results are listed on the following table (mean value, max. and min. value).

<table>
<thead>
<tr>
<th>Characteristics of the Specimen</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile of the tube</td>
<td></td>
</tr>
<tr>
<td>ISML 9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>ISML 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A rough estimation of the scatter (as in Section 3.9.1) for tensile and compression tests is given in the following table.

<table>
<thead>
<tr>
<th>Profile of the tube</th>
<th>Type of Test</th>
<th>Tension (ISML)</th>
<th>Compression (Euratom)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_u$</td>
<td>$e_{pb}$</td>
<td>$S'_u$</td>
</tr>
<tr>
<td>ISML 9</td>
<td>17%</td>
<td>118%</td>
<td>3%</td>
</tr>
<tr>
<td>ISML 12</td>
<td></td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>All finned tubes</td>
<td>43%</td>
<td>166%</td>
<td></td>
</tr>
</tbody>
</table>

We notice that the scatter is always lower in compression. Moreover this last type of test is easier to perform for production control and allows the values of elongation to be obtained more precisely, which lowers the scatter.

3.3.2.3 Burst tests

Burst tests as production control (Euratom results)

Sixty burst tests have been done on two main profiles in SAP 7%. The test conditions are similar to those for smooth tubes (see Section 3.3.1.2). For the calculation of tangential stress, the thin-wall formula $\sigma_t = \frac{P \cdot D_l}{2 \cdot t}$ was consistently used, "t" representing the minimum wall thickness (i.e. without fins) of the tube considering a medium tolerance. The results are assembled on the following table (mean value, max. and min. value).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Number of specimens</th>
<th>Burst pressure kg/cm²</th>
<th>Tangential rupture stress $\sigma_t$(kg/mm²)</th>
<th>scatter %</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISML 9</td>
<td>30</td>
<td>48 (44 to 50.5)</td>
<td>5.55 (5.1 to 5.8)</td>
<td>12.5</td>
</tr>
<tr>
<td>ISML 12</td>
<td>30</td>
<td>69 (64 to 74)</td>
<td>5.6 (5.2 to 6.0)</td>
<td>14</td>
</tr>
</tbody>
</table>
Most ruptures occurred at the bottom and along one of the higher spacer fins. The comparison between smooth extruded and cold drawn tubes and finned extruded tubes of SAP 7% is reported in the table below.

<table>
<thead>
<tr>
<th>Profile of the tube</th>
<th>Number of specimens</th>
<th>Tangential rupture stress (kg/mm²)</th>
<th>Scatter %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth tube</td>
<td>13</td>
<td>5.2</td>
<td>35%</td>
</tr>
<tr>
<td>ISML 9</td>
<td>30</td>
<td>5.55</td>
<td>12.5%</td>
</tr>
<tr>
<td>ISML 12</td>
<td>30</td>
<td>5.6</td>
<td>14%</td>
</tr>
</tbody>
</table>

The values of rupture stresses for finned tubes are about 7% higher and the scatter is only the half.

The ratio between tangential and longitudinal stresses in finned tubes as compared with smooth tubes is given below.

<table>
<thead>
<tr>
<th>Type of tube</th>
<th>Tension test</th>
<th>Burst test</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>6.3</td>
<td>5.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Finned</td>
<td>9</td>
<td>5.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

This result shows that in finned tubes the difference in mechanical strength in the two directions is higher than in smooth tubes.

3.3.2.4 Influence of internal artificial defects on the transverse mechanical properties of finned tubes.

Preliminary studies have been carried out at 450°C on finned tubes (ISML 9) with internal artificial defects machined with a constant profile tool (Ref. 62 bis). All tubes were first ultrasonic tested to ensure that they were free from any natural defect and their thickness between every fin carefully measured. The form and dimension of the defects are shown on Illustration 7. Its location is represented on Position 3. A macrography shows on Illustration 8 the real profile obtained. Ten specimens have
INTERNAL DEFECTS
MACHINED IN FINNED TUBES

Shape and dimensions of the defect

Position of the defect

Illustration 8 Artificial defect 0.15 mm depth machined on finned tubes (magnification 50)
been tested for each type of defect. The results are summarized in the table below. The tangential stress is calculated using the wall thickness measured on the ruptured generatrix; most ruptures occur along and at the bottom of a spacer fin; only 30% of all the tubes ruptured on the defect.

<table>
<thead>
<tr>
<th>Depth of defect (mm)</th>
<th>Mean value of tangential stress (kg/mm²)</th>
<th>Scatter (%)</th>
<th>Decrease of strength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.52</td>
<td>6.5%</td>
<td>0</td>
</tr>
<tr>
<td>0.05</td>
<td>5.45</td>
<td>8.5%</td>
<td>1.3%</td>
</tr>
<tr>
<td>0.10</td>
<td>5.40</td>
<td>10.5%</td>
<td>2.4%</td>
</tr>
<tr>
<td>0.15</td>
<td>5.34</td>
<td>12%</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

We notice that the scatter increases with increasing the depth of the defect, but remains lower than in production control tests. The mean values of the rupture stresses show a slight decrease of only 3.3% which is of no real significance due to the large scatter.

3.3.2.5 Fatigue tests under internal gas pressure

Experimental conditions

The test arrangement is similar to the one used for smooth tubes (see Section 5.1.2). Experiments have been carried out on test specimens 300 mm length of finned tubes profile ISM 9 free from natural defects (U.S. controlled) but having artificial internal defects as described in the previous section. The pressure rose from 1 kg/cm² up to the preselected value in approximately 1 minute and was decreased to the initial value nearly instantaneously.

Results

As previously, the tangential rupture stress is calculated with the classical $\sigma_t = \frac{P \cdot D_i}{2 \cdot t}$ formula, "t" being the thickness along the line of rupture. As a matter of fact, 66% of all the
tubes ruptured outside the zone of the artificial defects. Most ruptures occurred at the bottom and along one of the three spacer fins. The results are reported on the diagram Fig. 119. We see clearly that the rupture stresses of tubes with defects of 0.05 and 0.10 mm and the most part of those of 0.15 are contained in the dispersion band of the values for tubes without defects. Such short longitudinal defects affecting 10% of the wall thickness do not seem to be very critical even in fatigue testing.

3.3.2.6 Creep tests in compression (Euratom results)

Test conditions

We used the Adamel TAC stress to rupture machines (as in Section 3.4.1.1) fitted with a cage system allowing work in compression. The test temperature was 460°C. Specimens were pieces of ISML 7 finned tubes of 40 mm length (cross section 138 mm²).

Results: The number of specimens tested at each stress is as follows

- 3.8 kg/mm²: 3 tests
- 4.0 kg/mm²: 3 tests
- 5.0 kg/mm²: 6 tests

In these conditions only three specimens at 5.0 kg ruptured after 21,817 and 2,039 hours respectively, all the others remaining unbroken after more than 4,000 hours. Similar experiments made on cylinders have not ruptured even under a stress of 5.0 kg/mm².

3.3.2.7 Gradual Evolution of Batch Quality

As for the bar production (see Figs. 89-91) we have plotted the tensile properties as a function of the batch number.

Fig. 113 concerns all the tubes as a whole and Fig. 114 profile No. 9 only.

A scatter range is clearly visible in all cases. However, over a long period there is a general tendency for the properties to increase.
3.3.3 Pressure Tubes

The main results obtained are given in Ref. 55.

3.4 Comparison Between Rods and Tubes

3.4.1 Smooth Tubes

Creep tests

The creep properties of SAP 4\textsubscript{\%} and 7\textsubscript{\%} are compared in Figs. 115 and 116 respectively. The critical stresses act in two different directions, relative to the fibrous Al\textsubscript{2}O\textsubscript{3} structure.

Thus, for rod material it is a longitudinal stress and for tube material (creep test with internal gas pressure) transverse. The following table for smooth tubes and rods can be drawn up for the ratio between these two stresses after 100 hr creep-rupture.

<table>
<thead>
<tr>
<th>Al\textsubscript{2}O\textsubscript{3} \text{%}</th>
<th>Slow testing (creep)</th>
<th>Fast testing (tensile &amp; burst tests) (Section 5.1.2 and 5.2.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$S_{10}/S_{tr} = 1.3$ to $2.1$</td>
<td>$S_{10}/S_{tr} = 1.25$</td>
</tr>
<tr>
<td>7</td>
<td>$S_{10}/S_{tr} = 1.35$</td>
<td>$S_{10}/S_{tr} = 1.2$</td>
</tr>
</tbody>
</table>

This ratio is compared to the fast testing ratio. It will be seen that the difference between the transverse and longitudinal strengths is greater during slow testing.

Tension tests

In Figs. 105-107 the properties of smooth tubes and extruded rods (position 1) are compared.

Generally speaking, it may be said that for smooth tubes the strains are lower for 20 and 450\^C and the stresses also for the 450\^C tests.

3.4.2 Finned tubes

Histograms of tensile tests of tubes and rods of SAP ISML 7\% at 450\^C are given in Fig. 117.
### Properties at 450°C

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$S_u$ (kg/mm²)</th>
<th>$e_{pb}$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>rod</td>
<td>7.6</td>
<td>4.4</td>
</tr>
<tr>
<td>tube</td>
<td>9.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Note the higher strength (18%) and lower ductility (a decrease of 27%) of the tubes.

3.5 Physical Properties

Since the aim of this report is mainly to describe the mechanical properties, a complete description of the physical properties will not be given. We shall limit ourselves to those which could be of immediate interest to the designer.

3.5.1 Young's Modulus

3.5.1.1 Experimental devices

3.5.1.1.1 Static methods

**Euratom tests:**

All these tests were carried out on a universal electrical Instron machine.

Tests at 20°C (Ref. 27, Fig. 92).

Test specimen diameter 4 mm, gauge length 25.4 mm, drawn from bars of 9.5 mm, extrusion ratio $E = 76$.

Elongation measured with the aid of a Wideman-Baldwin inductive extensometer type PSH 8 MS (magnification 500 x). The results were taken from diagrams plotted by the xy recorder of the Instron machine (load as a function of specimen elongation).

**High temperature tests** (Ref. 30, Fig. 93)

Test specimens: 1st test specimen (Fig. 3) diameter 4 mm, length 30 mm.

2nd test specimen diameter 4 mm, length 5 mm.
We used a differential method involving the use of two test specimens of different lengths so as to eliminate the effects due to the deflection of the frame of the machine. The furnace kept the temperature constant at ± 10°C.

ISIL tests (Ref. 6).

This laboratory used test specimens 10 mm in diameter and 100 mm long drawn from bars 16 mm in diameter (extrusion ratio E = 26.6). The testing machine was an Amsler hydraulic machine. The elongations were measured with the aid of a Martens-type extensometer (magnification 500 x). The furnace was set to ± 2°C.

3.5.1.1.2 Dynamic methods

Euratom tests (Ref. 29, Fig. 92)

These were performed by internal damping on a Bordoni-type machine (Ref. 24) designed by Euratom.

ISIL tests (Ref. 3, Fig. 92)

The apparatus used was of the Bordoni type (Ref. 24) with electrostatic excitation. The test specimens were cylinders 8 mm in diameter and 160 mm long obtained by double extrusion (extrusion ratio E = 107). The measurements were made under a vacuum of 1.5 mm Hg. The damping of the oscillations was observed with the aid of an oscilloscope.

3.5.1.2 Results

3.5.1.2.1 Young's modulus at 20°C as a function of the oxide content (Fig. 92)

Young's modulus increases with the oxide content.

Static method:

- Euratom tests
  Each point represents an average of five measurements.
  The average scatter is of the order of ± 7%.

- ISIL tests
  Each point represents the average of two tests. The scatter is much smaller.
Comparison of the two results:
The values obtained by Euratom are higher by about 4\% than those of ISML over the whole range of Al$_2$O$_3$ contents.

Dynamic method:
As foreseen, the dynamic Young's modulus is higher than the static Young's modulus (about 12\%).

3.5.1.2.2 Variations in Young's modulus with the temperature for four SAP ISML contents.

Static method:
For the SAP 4\%, the Euratom results show a discontinuity between 250 and 350°C. The lack of agreement with the ISML results is of the order of 3\%.

Dynamic method:
The dynamic Young's modulus was only determined on SAP 4\%, and is about 20\% higher than the static modulus.

3.5.2 Linear Thermal Expansion
3.5.2.1 Test conditions
- Apparatus: A Chevenard-type dilatometer with photographic recording was used. It was a special Adamel Type 55 equipped to operate under vacuum or in controlled atmosphere.
- Test specimen: A 50 cm long specimen was used for measuring the expansion in the extruded direction and a 25 cm specimen for the perpendicular direction.
- Experiment: This was conducted in argon atmosphere with an increasing temperature of 60°C/hr. The magnification K was 150 or 300 times.

3.5.2.2 Experimental results
The results obtained perpendicular or parallel to the extrusion direction were practically identical. The results for the latter direction are given in Fig. 94. The values for the linear thermal expansion are plotted as a function of the oxide content for several temperature ranges between 20 and 500°C.
It was possible to establish the equation below expressing the length of SAP samples of different grades as a function of the temperature:

\[
\begin{align*}
\text{SAP ISML 4}\% \quad l_t &= l_0 (1 + 21.32 \cdot 10^{-6} t + 9 \cdot 10^{-9} t^2) \\
\text{SAP ISML 7}\% \quad l_t &= l_0 (1 + 20.38 \cdot 10^{-6} t + 9 \cdot 10^{-9} t^2) \\
\text{SAP ISML 10}\% \quad l_t &= l_0 (1 + 19.73 \cdot 10^{-6} t + 9 \cdot 10^{-9} t^2) \\
\text{SAP ISML 14}\% \quad l_t &= l_0 (1 + 18.93 \cdot 10^{-6} t + 9 \cdot 10^{-9} t^2)
\end{align*}
\]

It can again be seen from these formulae that the thermal expansion drops as the oxide content increases.

3.5.3 Electrical Resistivity

3.5.3.1 Test conditions

Euratom laboratory (Ref. 50)

The tests described were performed with a double Thompson bridge. The electrical resistance of the bridges was verified to an accuracy of better than \(2 \cdot 10^{-4}\). The test specimen is a cylinder 6 mm in diameter and 80 mm long. The sample holder was designed specially in order to increase the relative precision of the gauge length up to \(0.1\%\). Under the above conditions, the relative error in the determination of the resistivity \(\frac{\Delta R}{R}\) is less than \(0.5\%\).

Euratom laboratory (Ref. 54)

The electrical resistivity was measured by the d.c. potentiometric method. The samples were mounted in series with a standard resistance, immersed in a thermostatic bath and the current flow then measured with a potentiometer. The limit accuracy in the determination of the current was that of the standard, i.e., \(2 \cdot 10^{-4}\). The samples were immersed in a thermostatic bath kept at \(25 \pm 0.05^\circ\text{C}\) and the potential drop between two knife edges measured with a five dial potentiometer. Care was taken to eliminate thermoelectric emf by reversing the current.

The samples were cylinders 4 mm in diameter and 50 mm long. The error affecting the dimensions can be estimated at \(<1\%\). All the samples had been annealed for two hours at \(550^\circ\text{C}\) in a high-vacuum furnace.
The resistivity at high temperature up to $500^\circ C$ was measured by determining the ratio between the resistances at the given temperature and at $25^\circ C$. The resistivity data at high temperature were corrected for the effect of thermal expansion.

As a coefficient of thermal expansion of SAP, a value of $24.10^{-6}$ cm/°C was taken which is independent of the orientation (Ref. 25).

The samples were heated in a high-vacuum furnace stabilized to $\pm 0.5^\circ C$, standardized thermocouples being used. The reproducibility of the electrical resistivity data was to within $2.10^{-3}$ and it can be assumed that the error affecting these values is $\leq 1\%$.

ISNL Laboratory (Ref. 9).

The classical d.c. potentiometric method was used, the testing specimen being connected in series with a calibrated resistance. The testing specimen is machined from an extruded plate ($30 \times 2.5$ mm) and annealed for 24 hr at $500^\circ C$. The tests were conducted up to $550^\circ C$ in a furnace with a temperature determination of $\pm 1^\circ C$. The accuracy of the readings of the potentiometer was $10^{-7}$. The relative scatter in the results observed in several tests in the same conditions did not exceed $3.10^{-4}$. The ratio $\frac{R_1}{R_{20}}$ was determined for every temperature and the absolute value of $R_{20}$ for every percentage of $Al_2O_3$.

3.5.3.2 Results

- Resistivity as a function of the oxide content at $20^\circ C$

(Ref. 50, Euratom, Fig. 95)

On this diagram we have also plotted the values determined by other laboratories. This diagram clearly shows that the absolute resistivity increases with the oxide content. Every test specimen was chemically analyzed, and there is a relatively high scatter in the oxide content.

The mean scatter of the resistivity is in the range of $\pm 3.5\%$. The values obtained in other laboratories for other batches are in the normal scatter range.
Resistivity as a function of the test temperature for different grades of SAP ISML (Refs. 9, 26 and 54, Figs. 96 and 97, Euratom and ISML results)

The electrical resistivity increased with temperature and the results obtained in the two laboratories are in good agreement.

Resistivity parallel and perpendicular to the direction of extrusion as a function of the oxide content at 100°C and 500°C

Euratom result (Ref. 54, Fig. 98)

The resistivity values increase with the oxide content, as seen above (Fig. 95). Moreover, the transverse resistivity is higher than the longitudinal one.

3.5.4 Thermal conductivity

3.5.4.1 Experimental procedure

Euratom laboratory (Ref. 53)

The apparatus is Euratom-built. The method is a stationary one, conducted with axial flow along a cylindrical sample. Armco iron was selected as the reference sample.

Euratom laboratory (Ref. 54)

For this present study, use was made of a new transient flow method developed to meet the specific requirements of our research. This method enables both the thermal diffusivity and the conductivity in a given direction to be determined and offers the advantage of using a known thermal capacity as a reference. Because the specific heat is a property known with much greater accuracy than the thermal conductivity, the method seems more reliable than those based on comparison with a standard thermal resistance.

Comparative determination on high purity nickel and aluminium samples with conventional steady state techniques and the methods described above resulted in close agreement, the difference being in all cases less than 6%.
ISML laboratory (Ref. 3)

The relative method employed by the US Bureau of Standards (Ref. 44) for use up to 600°C was adopted. The method consists in measuring the thermal gradient along two cylindrical samples, one of them being the material to be tested and the other one a reference sample (in this case lead). The two samples are welded together at the end and placed in a metallic tube. A complete description of this apparatus is given in Ref. 66.

3.5.4.2 Results

Thermal conductivity plotted as a function of the temperature (Figs. 99, 100 and 101).

The ISML laboratory expressed the thermal conductivity of SAP ISML as a proportion of that of aluminium (Raffin 99.995%).

The apparatus used by the Euratom laboratory (Ref. 53) was tested on 99.999% aluminium and the values obtained plotted in Fig. 99 are in good agreement with the literature.

From Figs. 99, 101, it can be seen that the conductivity falls compared with that of aluminium as the oxide content increases.

In conclusion, it may be said that the conductivity seems to drop as the temperature rises but the results obtained by the three laboratories do not seem to be in good agreement.

Thermal conductivity, longitudinal and transverse at 100°C and 500°C versus the oxide content (Ref. 54, Figs. 102 and 103)

The transverse conductivity is always lower than the longitudinal one. The difference increases as the oxide content rises, but is fairly constant for the temperature related.

Thermal conductivity, longitudinal and transverse, of SAP ISML 10% versus the temperature (Ref. 53, Fig. 99)

The transverse conductivity is 25% lower than the longitudinal one and this difference decreases slightly as the temperature rises.
3.5.5 Density

The values for the density versus the percentage of Al$_2$O$_3$ are plotted in Fig. 104.

These results concern batches of SAP ISML which are representative of the production from 1960 to 1966. The scatter of the results does not exceed ± 0.2%. It can be seen that the density is proportional to the percentage of Al$_2$O$_3$. Fig. 104a shows results obtained at Risø Institute (Ref. 41). The density of the materials was determined according to Ref. 39. The data are averages of 3-6 measurements.
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Alfred Nobel
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