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Use of Neutron-Absorbing Additions to the Coolant for Shutdown of Fast Sodium-Cooled Reactors

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Abstract

In this work, an independent shutdown system for sodium cooled reactors is discussed. The principle of operation consists in poisoning the coolant with metals soluble in sodium, i.e., miscible metals. Of all the materials considered lithium with higher Li^6 concentrations is most suitable. The miscibility of lithium with sodium is safeguarded for the conditions of concentration if the temperature do not fall below 150°C. After the coolant has been poisoned, lithium can be separated from sodium by simple methods. The corrosion problems which may arise play no major part. Calculations show that already small concentrations of Li^6 in the coolant of a breeder reactor give rise to considerable shutdown reactivities. For the sodium-cooled 300 MWe reactor Na2, a technical concept is indicated by means of which the primary cycle can be poisoned in emergencies. The main principle consists in an automatic self-dosage of the poisoning by a Venturi nozzle. Quick-acting lithium injectors bridge the start-up phase of the automatic poisoning system.

Zusammenfassung

In dieser Arbeit wird ein unabhängiges Notabschaltsystem für natriumgekühlte Reaktoren zur Diskussion gestellt. Das Prinzip besteht darin, das Kühlmittel mit in Natrium löslichen, d.h. mischbaren, Metallen zu vergiften. Von allen betrachteten Materialien ist das Lithium mit höheren Li6-Konzentrationen insgesamt am besten geeignet. Die Vermischbarkeit des Lithium mit Natrium ist für die fraglichen Konzentrationsverhältnisse gesichert, wenn die Temperaturen 150°C nicht unterschreiten. Nach erfolgter Vergiftung des Kühlmittels, läßt sich das Lithium vom Natrium mit einfachen Methoden trennen. Die auftretenden Korrosionsprobleme spielen keine bedeutende Rolle. Berechnungen zeigen, daß schon sehr kleine Konzentrationen von Li6 im Kühlmittel eines Brutreaktors erhebliche Abschaltreaktivitäten verursachen. Für den natriumgekühlten 300 MWe Reaktor Na2 wird ein technisches Konzept angegeben, mit dessen Hilfe die Vergiftung des Primärkreislaufes im Notfall vorgenommen werden kann. Das Hauptprinzip besteht in einer automatischen Selbstdosierung der Vergiftung durch eine Venturidüse. Schnell wirkende Lithiuminjektoren überbrücken die Anlaufphase der automatischen Vergiftungsvorrichtung.

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1. INTRODUCTION

In general, fast sodium-cooled reactors are shut down by means of shutdown rods. These rods contain the absorber material (e.g., B_4C, where the boron may be enriched in B10). Although this type of shutdown system is regarded as relatively reliable, there are reasons for the discussion of completely different shutdown systems.

Such reasons are:

1) The operation of a reactor may give rise to conditions which render a shutdown by solid shutdown rods impossible, e.g., in case of a deformation of the channels in which the shutdown rods move, or as a result of solid corrosion product deposits on important parts of the shutdown system.

2) There is a general wish for diversity and redundance with respect to reactor shutdown systems.

We therefore discuss a shutdown system which is not dependent on any firm geometry within the core.

In principle, amorphous neutron absorbing substances (suspensions and liquid metals) should be introduced into the system by means of the sodium coolant. The most suitable substances are liquid metals which mix with sodium /‾1_7. Liquid lithium is shown to be a suitable shutdown substance for fast sodium cooled reactors. The application of the proposed shutdown system is based upon the following preconditions:

1) The normal shutdown system fails.
2) The core is permeated essentially by the sodium coolant.
3) Any deformations extend only over the areas of core and blanket.

2. CRITERIA FOR THE CHOICE OF THE ADDITIVES

When using liquid metals as the neutron absorbers, the following requirements should be fulfilled:

1) High neutron absorption cross section,
2) miscibility with sodium,
3) no corrosive action upon the structural material,
4) low melting point - high boiling point,
5) high specific heat,
6) easy removal from the coolant cycle.

These requirements restrict the number of possible absorber materials /‾2,3,4_7. In Table I, the metals with a low melting point and high absorption cross section are compiled.

Because of their corrosive action on the structural material, Zn, Cd, Sn, Sb, Se, and Tl must be excluded from among these metals. Some metals form intermetallic compounds with a high melting point with sodium and the rise of the liquidus curve is very steep, which makes the use of Ga, In, Sb, Se, and Te impossible.

Mercury has prohibitively high vapor pressure at the operating temperature of the reactor.

What remains are the alkali metals lithium, rubidium, and cesium. However, with rubidium the absorption effect will be too small. If one considers the possibilities of separating these materials from sodium, liquid lithium seems to be the best neutron absorbing additive to the sodium coolant.

It should be remarked that the use of lithium (salts soluble in water) is proposed as a neutron poison for thermal reactors /‾5,6,7_7.

3. MIXED Na-Li, Na-Rb, Na-Cs SYSTEMS

In the discussion of liquid metals as neutron absorbing additives the properties of the mixed systems produced should be considered. Initially, the properties of the pure components will be described.

3.1 Properties of the Pure Metals

The physical data of pure lithium, rubidium, and cesium are summarized in Table II.

3.2 The Phase Diagrams of Na-Li, Na-Rb, and Na-Cs

3.2.1 Na-Li

In the Na-Li system there is a miscibility gap from 3.8 at.% Na (=11.6 wt.%) to 86.9 at.% Na (=95.6 wt.%) in the liquid state /‾8 - 11_7. The miscibility gap closes above 380°C at about 45 at.% Na. There is a eutetic point at 96.3 at.% Na (98.9 wt.%) and 93.4°C; Fig. 1 /‾8 - 11_7.

3.2.2 Na-Rb and Na-Cs

The Na-Rb system has a eutetic only at 75.5 at.% (92 wt.%) Rb and -5°C. There are no indications of an intersolubility in the solid state, Fig. 2. Fig. 3 shows the phase diagram of Na-Cs. There is a eutetic at 75 at.% (94.5 wt.%) Cs and -29°C. The Na_2Cs compound discovered decomposes at -8°C /‾8_7.

3.3 Corrosive Action on Structural Material

The use of lithium as a shutdown medium requires the provision of non-corrosive storage tanks for pure lithium. In addition, the compatibility of a Na-Li melt with the structural materials of the reactor must be taken into account.
It is known from the literature [2,4] that pure lithium, as regards its corrosive properties, is similar to sodium and potassium but, on the whole, more aggressive than these alkali metals [12 - 15]. However, since there are special reactors with pure lithium as the coolant, it seems to be possible to solve the corrosion problem, as experimental investigations have shown. [16 - 19]
This is indicated also by the operation of heat pipes of Nb-Zr and Ta with lithium as the working fluid at temperatures between 1,500°C and 1,600°C for more than 1,000 hours of operation [19].

The corrosive action of the liquid Na-Li mixture on the structural materials of the reactor should play no part, because the sojourn time of the Na-Li melt in the reactor system proper should generally be short as against the life of the reactor. Moreover, sodium is the main component of the Na-Li melt. The final clarification of this problem would require a number of additional experimental investigations to be carried out.
Rubidium and cesium exhibit a behaviour similar to that of sodium.

3.4 Possibilities of Separating the Absorbing Additives from Sodium

In order to start up the reactor after an emergency shutdown it is necessary to remove the neutron absorbing additive from the sodium coolant.
This could be achieved best by a mixed system of limited solubility in the liquid state in which the components demix above their solidification points.
The phase diagram of the Na-Li mixed system allows partial separation of lithium from sodium, which is not possible with rubidium and cesium.
The demixing curve in the sodium-lithium phase diagram extends into the temperature area below the points of solidification of the components.
The eutetic on the sodium side is at 3.7 at.% (=1.1 wt.%) lithium, according to values from the literature [8,9]. Hence, a complete separation of lithium from sodium can be achieved neither by filtration nor by slow

cooling, as has been confirmed in individual experiments by the authors. Therefore, an additional process will have to be employed for the complete separation of lithium from sodium, i.e., a selective oxidation of lithium will be carried out. Nitrogen is a material particularly well suited to this process, because sodium does not react with nitrogen [4], but with lithium. Though, according to some data in the literature, the lithium-nitrogen reaction should occur at a high rate already at low temperature [4], experiments conducted by the authors showed that the higher rate of reaction will not begin until around 500°C. According to [20], there is a strong reaction between lithium and nitrogen at temperatures between 450°C and 460°C. A faster reaction between lithium and nitrogen in a sodium-rich melt will require nitrogen bubbling through the melt so as to cause a high degree of mixing. The Li_3N formed can be filtered off through a frit with an average pore size of 5 µ (cf. [14]). Other selective oxidizing agents besides nitrogen, i.e., all those reactants which have a greater affinity to lithium than to sodium, e.g., O_2, F_2 [21], can be used as well; however, the feed would have to be metered carefully. In a separation by means of hydrogen it should be taken into account that also sodium forms a hydride which reaches a dissociation pressure of 1 at. at around 425°C [22]; lithium hydride is more stable by contrast and exhibits a higher decomposition pressure only at the melting point [23]. In addition to pure gases as reactants one could also envisage an exchange reaction

$$NaX + Li{-}Na \rightarrow LiX + Na + NaX \longrightarrow$$

Sodium fluoride appears to be a suitable reactant.

4. ISOTOPE SEPARATION

Since Li^6, which is contained in natural lithium at a rate of 7.42%, has the main absorptive effect, it would be desirable to use this isotope as a shutdown medium in the highest possible concentration. Since Li^7 is an important coolant for space reactors, special attention is already being devoted to the possibilities of separating the lithium isotopes [24].

The following methods of separating lithium isotopes will be employed [25]:

1) Ion exchange of Li-amalgam by means of a solution of lithium (e.g., LiCl, LiBr) in absolute ethanol [20,26], in dimethyl formamide and in tetrahydrofurane.
2) Separation by ion exchangers, such as zeolites, zirconium phosphates, sulfonate resins [24,27].
3) Electrolysis of aqueous solutions on a mercury electrode [20, 28].
4) Electrolytic transfer in molten salts [26, 29].
5) Molecular distillation [30].
6) Separation by viscous disturbances of molton lithium [31].
7) Electromagnetic separation (mass spectrometer [20,22]).

This compilation shows that there are several methods of obtaining lithium with high Li^6 concentrations. The price is indicated in [33]. According to that reference, 11 kWh/g of lithium is required to produce Li^7 (99,974%) in a separation column of 22.8 cm length.

5. REACTIVITY EFFECTS OF THE MATERIALS LITHIUM, RUBIDIUM, AND CESIUM

The reactivity effects were determined with one-dimensional (radial) multigroup diffusion calculations [34] using 26 energy groups.
The Na1 (1,000 MWe) [35] and Na2 (300 MWe) [36] reactors calculated have cylindrical geometries. The cores have two zones in each case in order to achieve power flattening.
The separated axial variable was taken into account by an axial buckling independent of the additions. The group set used is described in [37].
To estimate the influence on reactivity of rubidium and cesium, group constants (see Table III)for neutron absorption were determined by means of [38 - 40].

5.1 Influence of the Reactor Size on the Reactivity Effect of Li^6

The reactivity influence of equal Li^6 concentrations in core and blanket is $\Delta k = 0.219$ for the large reactor (Na1) and $\Delta k = 0.200$ for the small reactor (Na2).

In this case, about 10 percent each of the sodium in the core and the blanket have been replaced by Li^6. The reactivity influence for equal Li^6 concentrations /¯$2.092 \cdot 10^{+21} \frac{\text{particles}}{\text{cm}^3}$ in the core and $1.255 \cdot 10^{+21} \frac{\text{particles}}{\text{cm}^3}$ in the blanket_7 is a little greater for the large reactor than for the small one.

All the reactivity values quoted below refer to the large reactor. The respective reactivity effect for the small reactor can be estimated quite well by the Δk values indicated.

5.2 Reactivity Effects for Various Materials

Table IV lists the reactivity effects resulting from a replacement by one of the materials under investigation of ten percent of the sodium in the whole reactor. Moreover, this table shows how many liters of absorber material are required in the core (core zone 1 and core zone 2) to achieve a reactivity effect of $\Delta k = -0.01$.

As is evident, pure Li^6 has a large reactivity effect. Only 14 l of Li^6 homogeneously distributed over core zones 1 and 2 cause a reactivity decrease by about 3 \$; the same effect is achieved with 25 l of lithium containing 50 percent of Li^6.

Although the absorption cross sections of cesium are only slightly smaller than those of Li^6 (Table III), the reactivity effect is markedly smaller, which is due to the considerably lower particle concentration /¯$\frac{\text{particles}}{\text{cm}^3}$¯7 of cesium (Table II).

The reactivity effects of rubidium, cesium, and pure Li^7 are rather small. Therefore, they cannot be used as shutdown materials. By contrast, lithium with a higher Li^6 concentration is well suited.

5.3 Space Dependency of the Reactivity Effect for Lithium with 50% Li^6

Table V shows the radial space dependency of the reactivity effect. As can be seen, the effect of the absorber material varies but a little within core zone 1, but strongly in the transition to core zone 2.

For the axial space dependency of the reactivity effect of lithium it is possible, after proper normalization, to take the axial reactivity dependency for rods containing B_4C from [35] or [36].

5.4 Determination of the Necessary Quantities of Li^6

Below, only the Li^6 material with the maximum shutdown effect will be considered. Fig. 4 shows the dependency on concentration of the reactivity effect increases linearly for concentrations up to some 5 vol.% (of displaced sodium), while the reactivity effect increases less markedly at higher concentrations.
1 vol.% of displaced sodium supplies a $\Delta k = -0.03$ (about 10 ¢ reactivity); at 3 vol.% of displaced sodium, $\Delta k = -0.09$ (about 30 ¢ of reactivity).

So, if a shutdown reactivity of some 30 ¢ [36] is desired, about 3 vol.% of sodium would have to be replaced by Li^6. 30 ¢ of shutdown reactivity with a homogeneous distribution of Li^6 over the whole core takes about 105 l of Li^6 for Na1 and about 26 l of Li^6 for Na2. Homogeneous poisoning of the entire cooling cycle would take about 23.4 m^3 with Na1 and about 18 m^3 of Li^6 with Na2.

6. POSSIBILITIES OF TECHNICAL EXECUTION

In case of failure of the normal shutdown system with mechanically moved shutdown rods the safety system of a corresponding design actuates coolant poisoning. This additional safety system should meet the following requirements:

1) The liquid absorber must be introduced into the core region sufficiently quickly, and it must be safeguarded that enough absorber material remains in the core region after shutdown.
2) It must be possible to dismantle all equipment for inspection and functional tests.
3) Involuntary poisoning of the coolant must be prevented by the suitable instrumentation, electronic decision and command circuits.

For investigation of the various possibilities of technical execution of such an additional safety system the fast sodium cooled breeder reactor described in the Na2 study [36] has been selected as an example. The main data of this reactor are compiled in Table VI. The necessary electronic systems (item 3) are not yet dealt with.

The emergency shutdown system as suggested here is to be employed only when all the other shutdown systems fail. Therefore, this system has the longest deadtime.

Longer deadtimes [36] necessitate either much higher rates for the shutdown reactivities in order not to exceed a certain damage mark (melting point of the fuel), or the controllable reactivity disturbances become smaller.

There are upper limits for the rates of shutdown reactivities; thus, in general, the controllable reactivity disturbances will become smaller with increasing deadtime. Within these limits, an additional shutdown system is quite capable of preventing major damage.

6.1 Principle Possibilities

In a disturbance, there are two typical cases of the change of sodium throughput through the core:

1) The coolant pumps continue to operate at their normal or a reduced rate.
2) After reactor shutdown the coolant pumps are shut down to avoid thermoshocks, as explained in [36].
   In this case, the sodium which continues to flow on because of its inertia will be slowed down in a characteristic way by friction losses and by a valve which closes in a defined way. This reduces the sodium throughput through the core until, finally, the onset of emergency cooling safeguards the minimum throughput required for afterheat removal. A qualitative representation of this process is shown in Fig. 5 [36, Fig. 7.13].

In both cases, the corresponding quantity of lithium must be added.

Coolant poisoning can be brought about in different principal ways:

1) One design might introduce the absorber into the core by mechanical pumps. This pump (geared pump, centrifugal pump) would feed the lithium from a storage tank into the coolant below the reactor.
2) The coolant is introduced into the reactor by means of gas pressure.

However, both possibilities require rather expensive control devices which would have to meter the quantities of lithium required in each case as a function of the changing sodium throughput. In addition, mechanical pumps raise the problem of energy supply, and gas pressure feed gives rise to the question where the displaced sodium could be accomodated in the reactor.

3) Another possibility, following [41], provides for lithium to be forced into tubes which extend through the reactor. In the normal state, these tubes are kept under a vacuum or an inert gas.

However, also this variant has some disadvantages: About 8 fuel element positions are required; this means increased neutron leakage from these tubes. Moreover, there is the possibility of a leak in the tubes through which the lithium can be released in an uncontrolled way.

4) The principle of poisoning we suggest is an automatic self-dosage of the absorber added to the coolant through the suction effect of a nozzle. In steady-state operation, the feed thus is adjusted automatically to the sodium throughput over a wide range. A disadvantage is the startup time of such a system and the delay resulting from the unavoidable transport time from the nozzle to the core.

To set off these disadvantages another system is envisaged which forces lithium into the core region through three lithium injectors from the top, thus supplying the necessary shutdown reactivity during the startup phase.

Our emergency shutdown system thus has the circuit diagram as outlined in Fig. 6.

In the ordinary case, the coolant flows through three parallel cycles, from the reactor through the coolant pump, the heat exchanger, and the shutoff device as well as the Venturi nozzle back into the core.

When the additional safety system is actuated, the lithium flows through electromagnetic valves from the storage tank to the Venturi nozzle.

In addition, the two parallel auxiliary cooling cycles with a non-return valve and the three lithium injectors are shown.

First the startup time of the Venturi nozzle is investigated. Let there be a steady-state flow in the tube which is supposed to supply a differential pressure ΔP.

After opening of the two valves, the liquid in the tube of length L and cross section area F is accelerated by the force $\Delta P \cdot F$.

Now

$$\Delta P \cdot F = \rho \cdot F \cdot L \cdot \frac{dw}{dt} + \zeta \cdot \frac{\rho}{2} w^2 \cdot F \qquad (1)$$

At the end of the transient a steady-state velocity w_o is established where:

$$\Delta P = \zeta \cdot \frac{\rho}{2} w_o^2 \qquad (2)$$

With

$$t_o = L/w_o \qquad (3)$$

one obtains from (1):

$$\frac{d(\frac{w}{w_o})}{d(t/t_o)} + C(\frac{w}{w_o})^2 = C \qquad (4)$$

where:

$$C = \frac{\Delta P}{\rho w_o^2} = \frac{\zeta}{2} \qquad (5)$$

Integration of (4) yields:

$$\frac{1}{2} \ln (\frac{w_o + w}{w_o - w}) = C \cdot \frac{t}{t_o} \qquad (6)$$

With $\Delta P = 0.25$ at, $L = 3$ m, $\zeta = 6.8$ (two valves), $\rho = 0.5$ g/cm^3 (Li), from (2) one obtains $w_o = 3.8$ m/sec, and from (6) the results presented in Fig. 7 in which the time constant $t_A = 0.23$ sec is defined.

After t_A 75% of the ultimate rate is reached in the feed line to the nozzle. This allows an estimate of the transport times up to the core.

In case the pumps continue to run, the transport time nozzle - edge of core is about 0.75 sec. This means that 0.88 sec after opening of the valves sodium enters the core with 50% of the rated poisoning; after 0.97 sec with 75% and after 1.09 sec with 90%.

After the closing device in the main line (Fig. 6) has been closed (closing time about one minute), the emergency cooling system starts with about 4% of the nominal throughput. Under the influence of the difference in densities, lithium continues to flow from the lithium storage tank at a decreasing rate, thus poisoning also the sodium circulating in the emergency cooling system.

6.2 Design and Construction

Self-dosing Poisoning Device:

Fig. 8 shows the installation in the reactor. Below the core, there are the lithium storage tank of some 18 m^3 volume, the Venturi nozzle which provides for self-dosing, and quick-opening outlet valves and tube connections to the Venturi nozzle. The valves are installed at different levels. In this way, an unequivocal direction of flow is defined in each case. When required, lithium flows out of the storage tank through the top valve and is sucked to the nozzle. The valve located at the bottom discharges sodium with the higher density into the storage tank.

The quick-opening outlet valves are actuated electromagnetically. When the reactor is shut down the valves can be dismantled for control and inspection. Moreover, the lithium storage tank can be filled with lithium and discharged through the tube installed in the valve units (displacement by inert gas). Through these filling tubes, any helium bubbles which might form can be removed also.

Quick-Acting Lithium Injectors:

The technical design of a lithium injector is shown in Fig. 9. A tube is routed through the reactor top cap into the inner core zone. This tube containse a piston formed by a metal bellows and expandable by a spring and gas pressure. The piston is released by means of the usual electromagnetic actuation. This piston forces the sodium into the core when needed. The lithium is separated from the sodium of the reactor system by a burst disk. Upon actuation of the piston, the lithium pressure causes the burst disk to rupture and the lithium column displaces the sodium contained in the guide tube. On the whole, some 18 l of lithium are introduced into the inner core zone through the three tubes, resulting in a negative reactivity contribution of about 12 $ with Na2. If one assumes that the burst disk ruptures 150 msec after actuation, the 12 $ will be reached after another 100 msec.

By way of conclusion it should be mentioned that care must be taken in emergency cooling of the reactor to prevent the temperature of the sodium-lithium mixture from falling below the liquidus line shown in Fig. 1, which can be achieved by controlling the temperatures and the heat removal.

7. SUMMARY

In this work, an independent shutdown system for sodium cooled reactors is discussed.
The principle of operation consists in poisoning the coolant with metals soluble in sodium, i.e., miscible metals.
Of all the materials considered lithium with higher Li^6 concentrations is most suitable.
The miscibility of lithium with sodium is safeguarded for the conditions of concentration in question if the temperature do not fall below 150°C.

After the coolant has been poisoned, lithium can be separated from sodium by simple methods.
The corrosion problems which may arise play no major part. Calculations have shown that already minute quantities of Li^6 in the core of a breeder reactor (105 liters with Na1, 26 liters with Na2) give rise to considerable shutdown reactivities. Poisoning of the whole primary cycle results in larger quantities of Li^6 (up to some 23.4 m^3 with Na1 and some 18 m^3 with Na2). Poisoning systems acting on but a small part of the primary cycle would require correspondingly smaller quantities of Li^6. For Na2, a technical concept is indicated by means of which the primary cycle can be poisoned in emergencies. The main principle consists in an automatic self-dosage of the poisoning by a Venturi nozzle. Quick-acting lithium injectors bridge the startup phase of the automatic poisoning system.

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Metal	σ_{th} [barn]	$\sigma_{(100KeV)}$ [mb]	Melting Point [°C]	Boiling Point [°C]	Suitable Structural Materials
Na	0.536	1.1	97.8	881	Fe, Steel, Cs, Ni, Nb, Ta, Mo, W
Li	71	1000	179	1317	Fe, Nb, Ta, Mo, Steel
Rb	0.73	50^+	38.5	700	same as Na
Cs	29	100^+	28.5	670	
Zn	1.1		419.5	907	Mo-Fe-alloy, Graphite
Cd	2537		320	767	Fe, Cr
Hg	380	60	- 38,9	357	Cr-steel, W, Mo
Ga	2.8	96	29.9	1983	W, Ta, Graphite
In	196	380	156.4	2000±10	Aust. Steel
Tl	3.4	24	303	1457	Mn, Steel
Sn	0.625	45	231	2270	Be, Ti
Sb	5.7	180	630.5	1380	
Se	11.7		220	688	
Te	4.7		452	1390	

Table I: Metals with low melting point and absorption cross section higher than sodium [2, 3, 4]

$^+$ at 400 keV

Physical Property	Lithium	Sodium	Rubidium	Cesium
Atomic Weight	6.94	22.991	85.48	132.91
Melting Point (°C)	186.0	97.5	39.00	28.5
Boiling Point (°C)	1336±5	880.0	688.00	705
Latent heat of vaporization, cal/g	4680	1005	212	146
Density, g/cm^3, at 20°C	0.534	0.97	39°:1.475	28.5°:1.84
100°C		0.886		
200°C	0.507			
250°C		0.850		
400°C	0.490	0.814		
600°C	0.474			
700°C		0.742		
Heat capacity, $\frac{cal}{g^\circ C}$, at 100°		0.3305	39°–126°: 0.0913	28.5°: 0.060
200°	1.0	0.3200		
600°	1.0	0.2998		
Thermal conductivity $\frac{cal}{sec \cdot cm^\circ C}$ at 200°C	0.09	0.1947	39°:0.07 50°:0.075	
Surface tension $\frac{dyn}{cm^\circ C}$ at 250°C		199.5		
Volume change on fusion % of solid volume	1.5	2.5	2.5	2.6

Table II: Physical properties of some liquid alkali metals

Group	Li6	Li7	Rb	Cs
1	0.06	$1. \times 10^{-3}$	1.24×10^{-3}	2.5×10^{-3}
2	0.10	0.	2.3×10^{-3}	4.2×10^{-3}
3	0.16	0.	3.8×10^{-3}	7.5×10^{-3}
4	0.25	$3. \times 10^{-6}$	6.48×10^{-3}	1.6×10^{-2}
5	0.30	$5. \times 10^{-6}$	1.35×10^{-2}	4.0×10^{-2}
6	0.50	$8. \times 10^{-6}$	2.11×10^{-2}	6.5×10^{-2}
7	2.00	2.5×10^{-5}	5.5×10^{-2}	9.0×10^{-2}
8	0.95	2.5×10^{-5}	7.0×10^{-2}	0.18
9	0.70	2.3×10^{-5}	0.1	0.3
10	0.85	3.0×10^{-5}	0.17	0.45
11	1.20	4.4×10^{-5}	0.3	0.70
12	1.80	6.5×10^{-5}	0.46	1.200
13	2.60	9.5×10^{-5}	0.7	2.00
14	3.90	1.4×10^{-4}	1.0	3.7
15	5.70	2.1×10^{-4}	1.5	5.4
16	8.40	3.0×10^{-4}	1.	8.0
17	12.0	4.4×10^{-4}	0.45	13.0
18	18.0	6.5×10^{-4}	6.5×10^{-2}	11.0
19	26.0	9.5×10^{-4}	4.5×10^{-2}	14.0
20	39.0	1.4×10^{-3}	3.7×10^{-2}	10.0
21	57.0	2.1×10^{-3}	4.5×10^{-2}	40.0
22	84.0	3.0×10^{-3}	6.0×10^{-2}	20.0
23	123.0	4.4×10^{-3}	9.0×10^{-2}	5.2
24	181.0	6.5×10^{-3}	0.14	5.5
25	264.0	9.5×10^{-3}	0.22	8.40
26	838.0	3.1×10^{-2}	0.60	24.0

Table III: 26-group Cross Sections for neutron absorption of the materials Li6, Li7, Rb, and Cs (energy structure like the 26-group set of Abagjan, Bazazjanc, Bondarenko, and Nikolaev)

	Li6: Li7:	100% 0%	50% 50%	7.42% 93.58%	0% 100%	Rb	Cs
-Δk, 10% of sodium replaced		21.9×10^{-2}	13.0×10^{-2}	2.59×10^{-2}	0.38×10^{-2}	0.67×10^{-2}	1.97×10^{-2}
Liter for $\Delta k = -0.01$		14.2	25.	120.	829.	466.	158.9

Table IV: Reactivity effects of lithium (for different isotopic compositions), rubidium, and cesium for reactor Na1

Radial Range R_1-R_2 [cm]	Core Zone	Liter of lithium (50% Li6) for $\Delta k = -0.01$
0. - 20.	zone 1	16.1
20. - 40.	zone 1	17.1
40. - 60.	zone 1	17.3
60. - 80.	zone 1	17.5
80. - 99.7	zone 1	19.5
99.7 - 120.	zone 2	27.9
120. - 141.	zone 2	64.7

Table V: Radial dependency of the reactivity effects for lithium (50% Li6) for reactor Na1

	Na1	Na2
Reactor Power Thermal, MW_{th}	2500	730
Electrical, MW_e	1000	300
Fuel Region, Height, cm	95.5	95
Diameter, cm	186	152.9
Thickness of Blanket Radial, cm	45	53.7
Axial, cm	40	40
Coolant Volume Fraction, Core, V/O	50	50
Blanket, V/O	30	30
Sodium Volume, Primary Cycle, m^3	780	633
Heat Exchanger, m^3	250	132
Tubes, m^3	48.8	70.5
Coolant Flow Rate, to/sec	13.184	3.2
Coolant Velocity in Core, m/sec	6.6	5.5
Pressure Loss in Core, at	4.25	2.5
Coolant Inlet Temperature, °C	430	380
Coolant Outlet Temperature, °C	580	560

Table VI: Data of sodium-cooled fast reactors Na1 and Na2

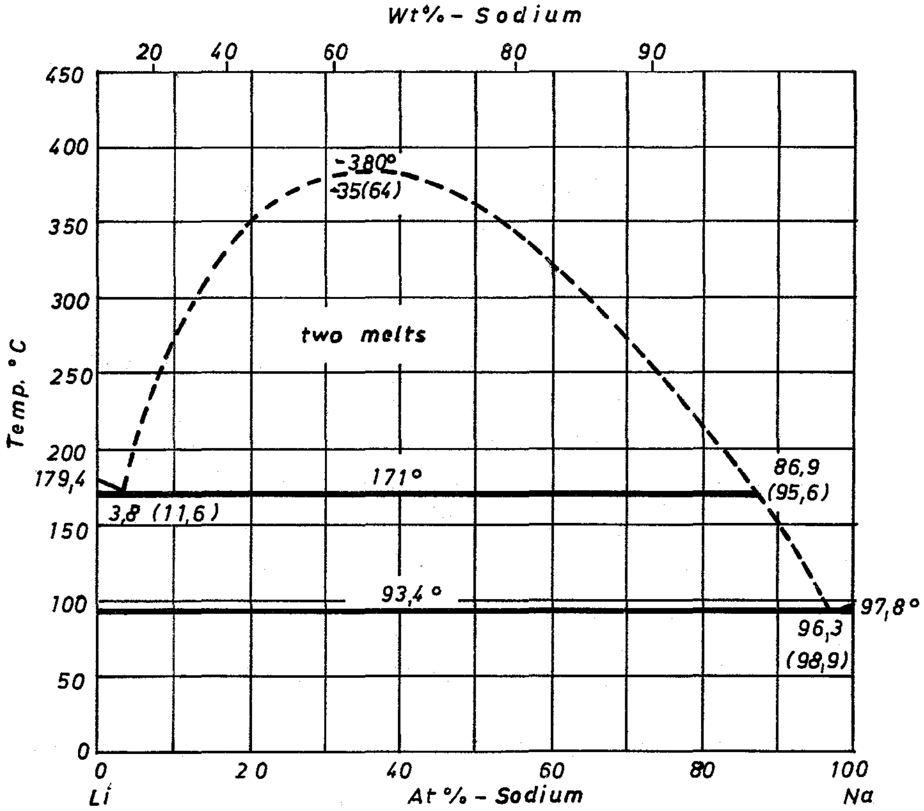


Fig. 1 Phase diagrams of the Lithium-Sodium system

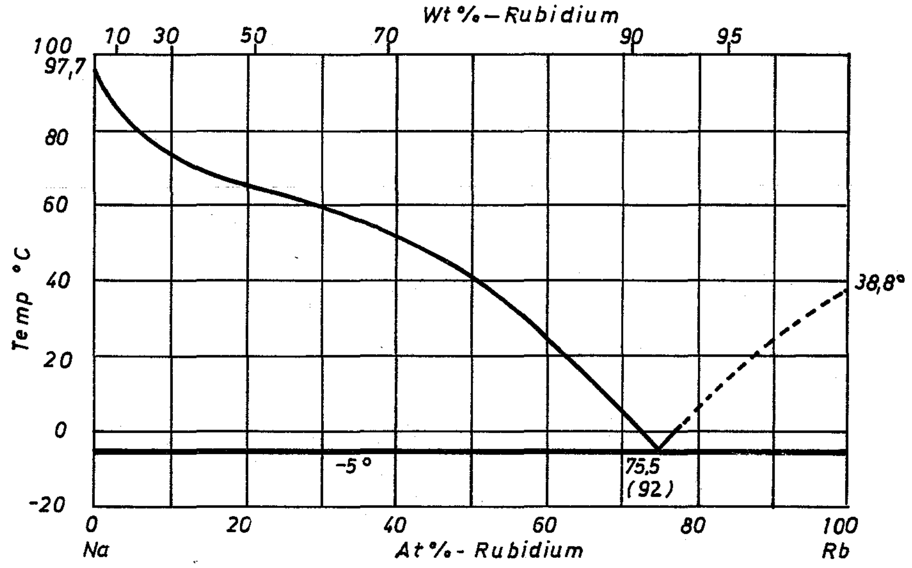


Fig. 2 Phase diagrams of the Rubidium-Sodium system

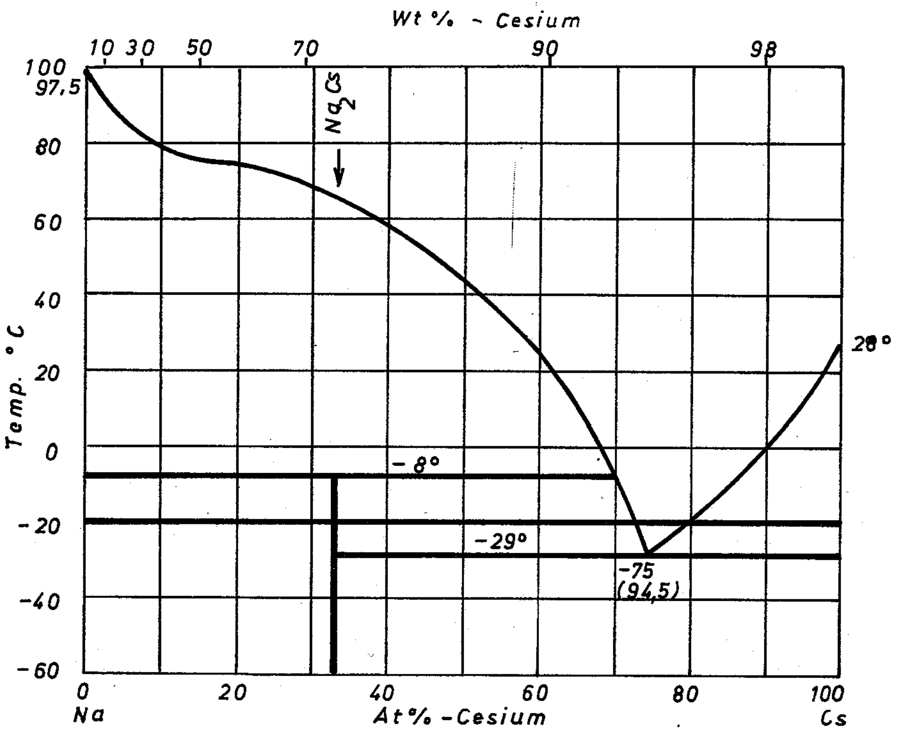


Fig. 3 Phase diagrams of the Cesium-Sodium system

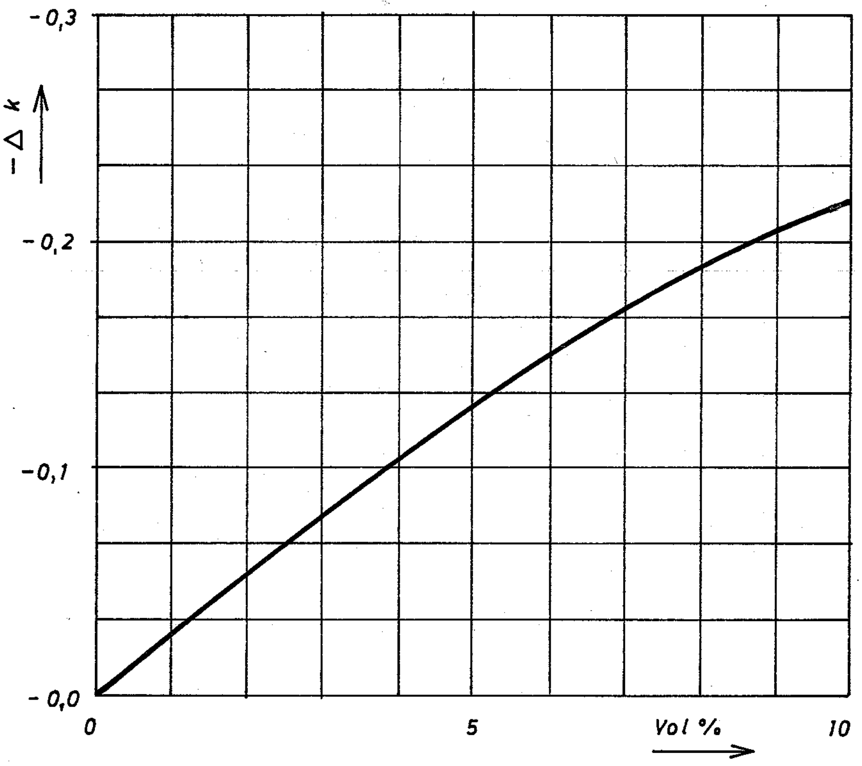


Fig. 4 Δk versus the Li 6 - volume fraktion of sodium

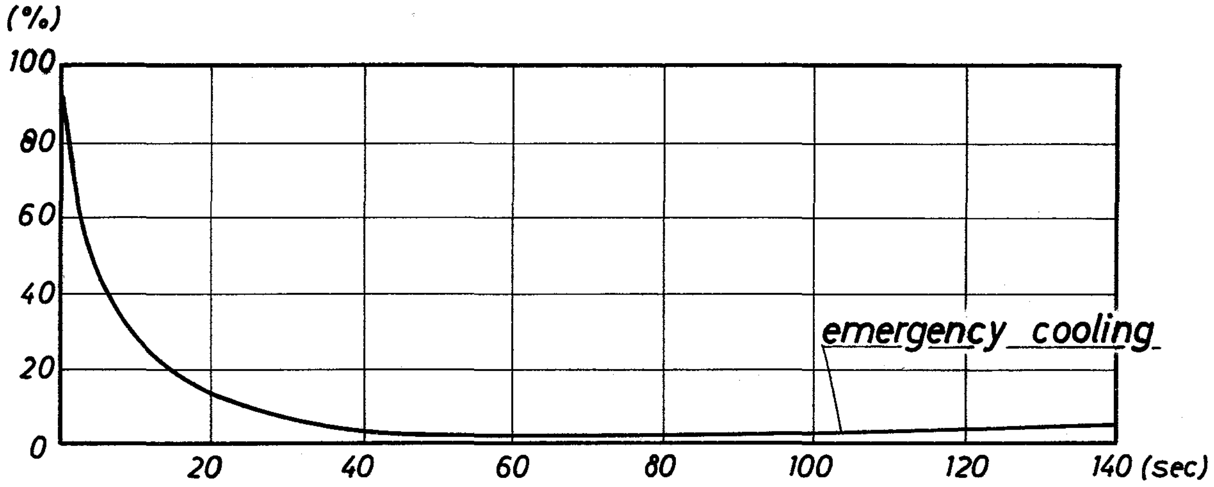
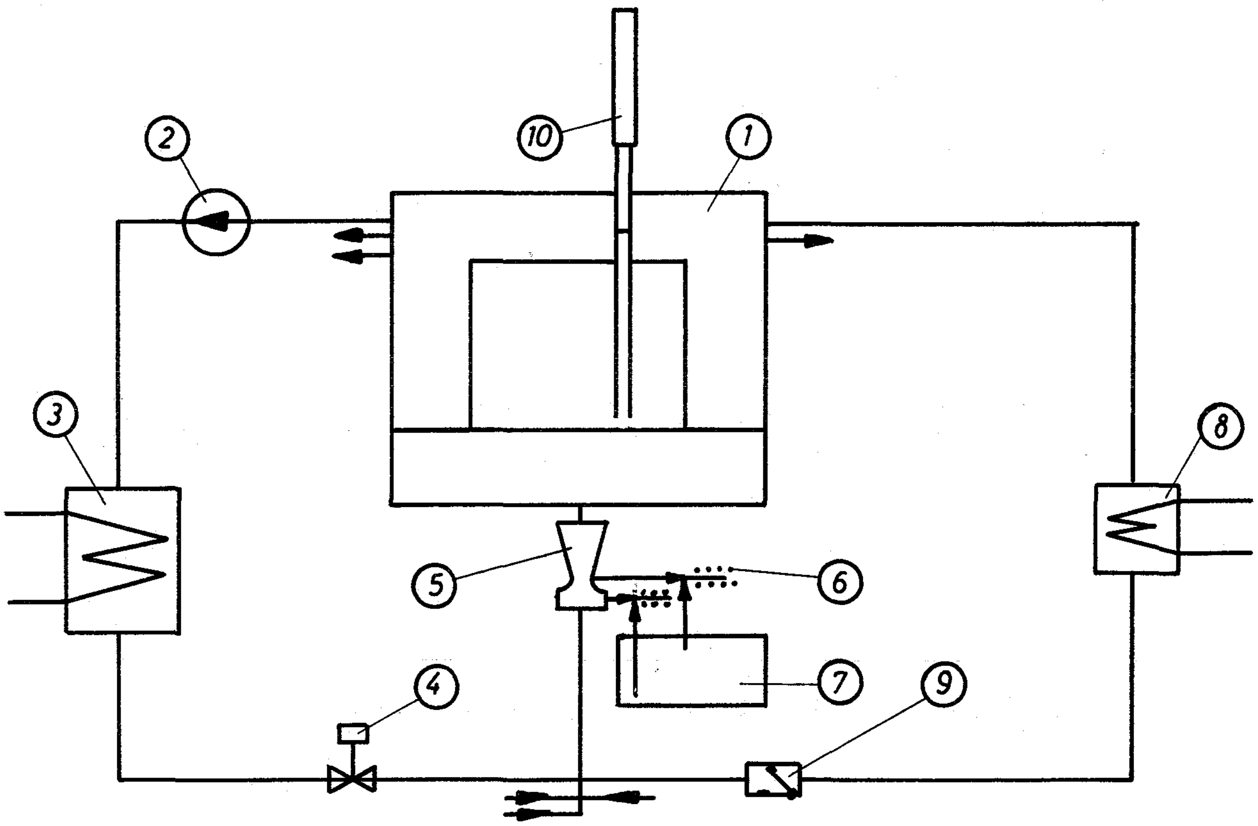


Fig. 5 Coolant flow after disconnection of main pumps
(Valves closing in 60 sec)



①	Reactor
②	Main Pump
③	Heat Exchanger
④	Stop Valve
⑤	Venturi Tube
⑥	Electromagn. Valves
⑦	Absorber Tank
⑧	Emergency Cooling
⑨	Nonreturn Valve
⑩	Li-Injector

Fig. 6 Circuit diagram

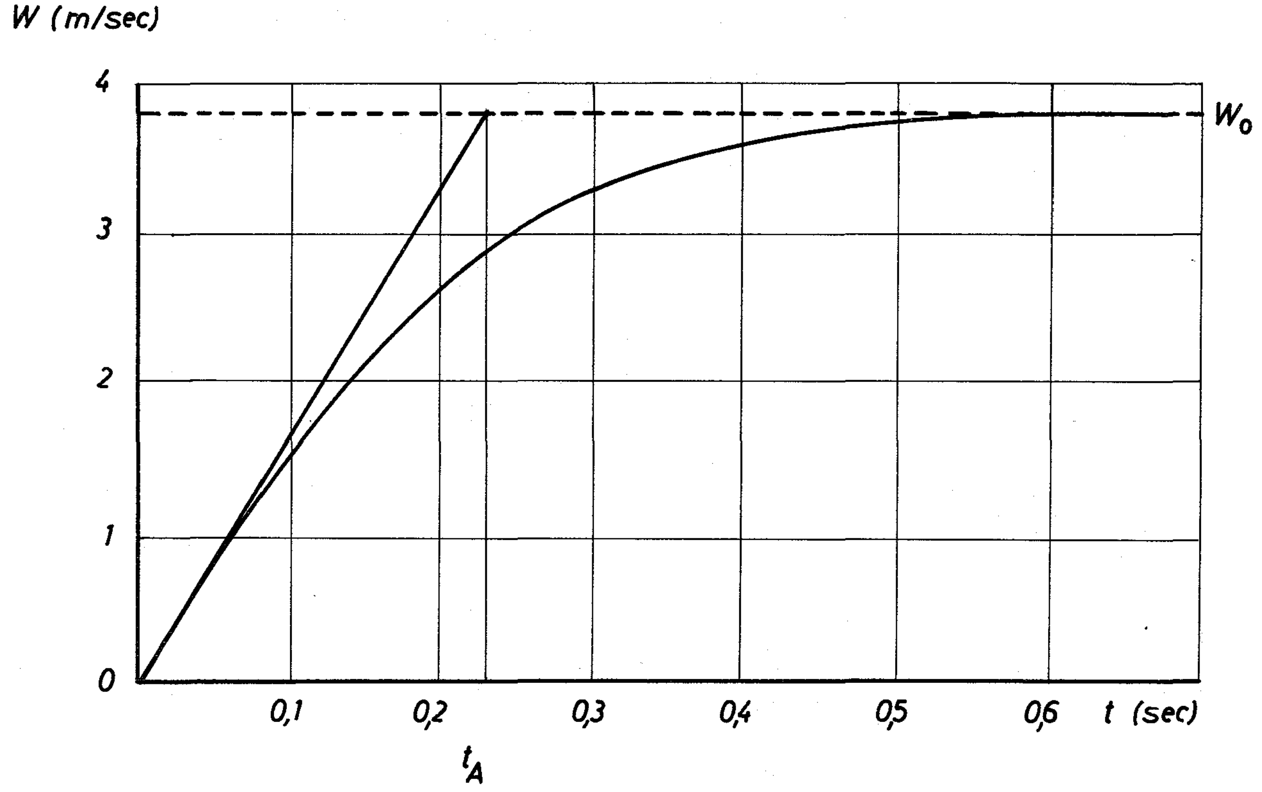
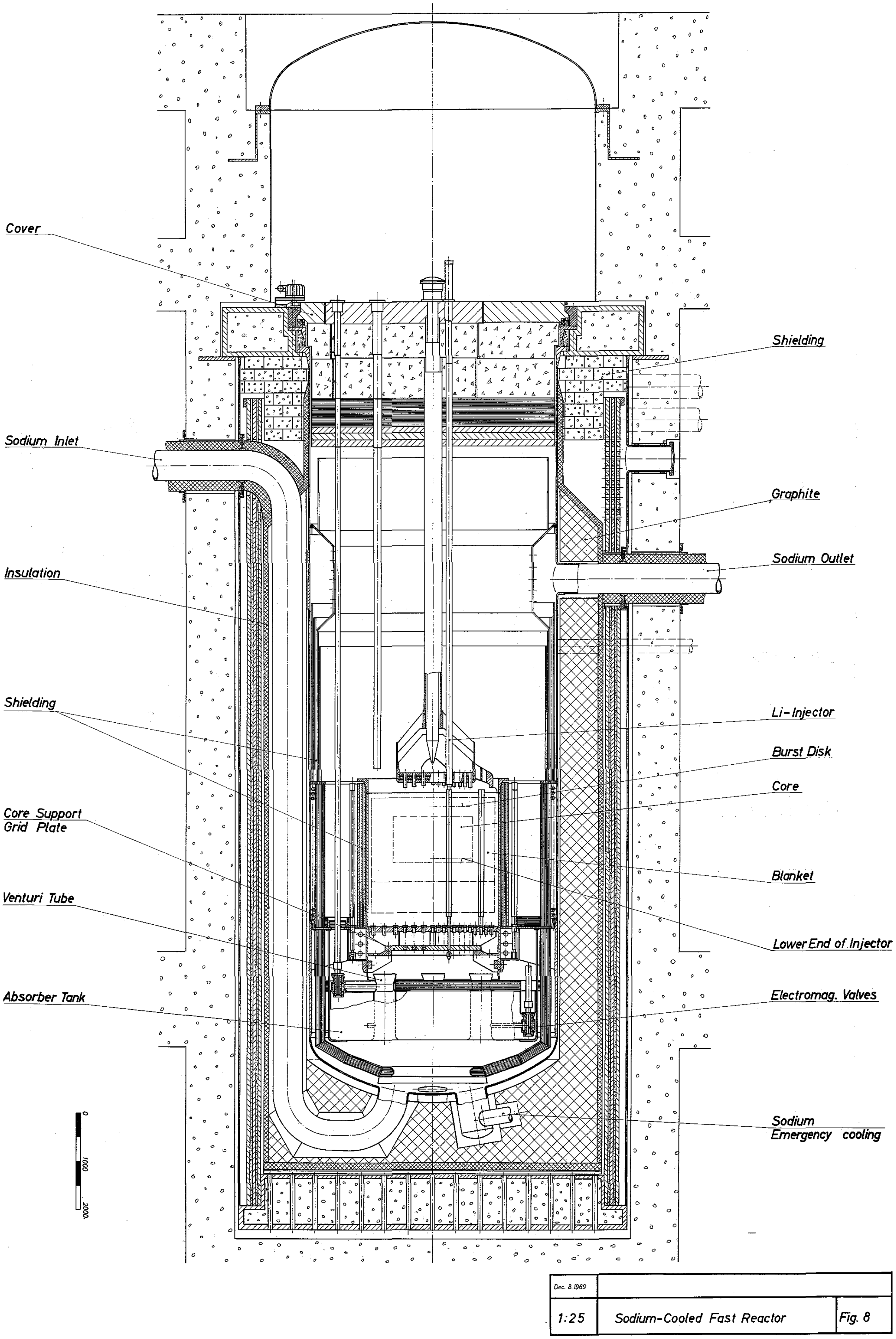
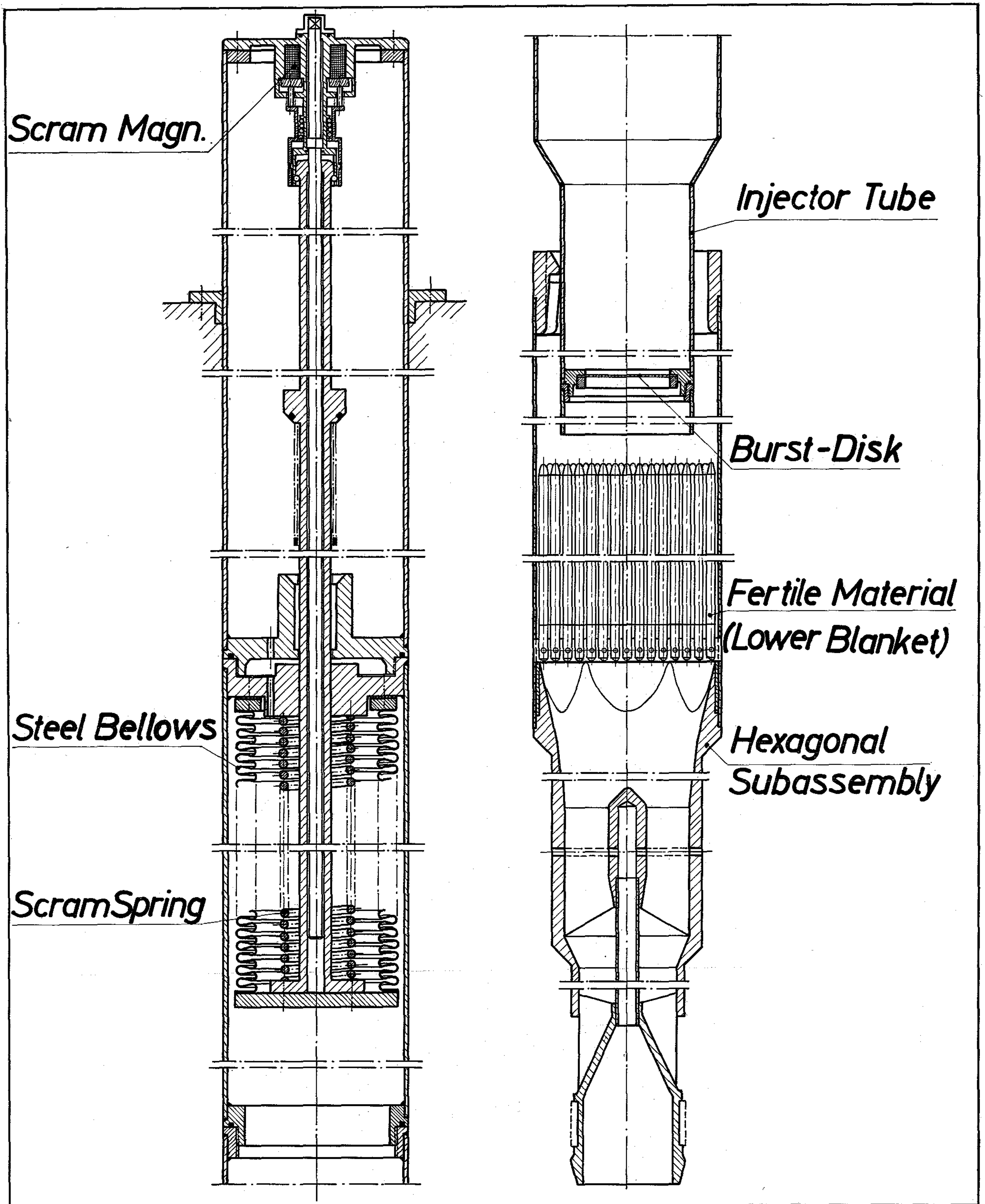


Fig.7 Velocity of lithium after valve opening



Dec. 8.1969		
1:25	Sodium-Cooled Fast Reactor	Fig. 8



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Litium-Injector

Fig. 9