RESEARCH PROBLEMS IN NUCLEAR PROPULSION

Part I - Nuclear Power Plants and Shielding

by Donald Bogart, Frank E. Rom, and Robert R. McCready

An airplane that could go to any point on the face of the earth and return at supersonic speeds would be an important military asset. We know that the flight range of aircraft powered by gasoline or jet fuel is limited by the weight of fuel they can carry.

Now, when fission of the uranium nucleus was announced, it was pointed out that one pound of uranium would produce as much heat as 2,000,000 pounds of gasoline (C-35911). It became apparent that the barrier to increased flight range could be broken by the use of uranium. With one pound of uranium doing the work of 2,000,000 pounds of gasoline, fuel weight no longer stands as a limit to flight range.

With so large an advantage in view, an effort is being made by the Atomic Energy Commission, the military services, industry, and the NACA to develop a nuclear propulsion engine. There are, of course, a great many difficult engineering problems that must be solved. What we plan to do today is discuss the nuclear propulsion engine, indicate some of its problems, and show how the NACA is contributing to their solution. I will describe briefly how a nuclear propulsion engine functions and the next two speakers will discuss the heat transfer and the materials problems associated with this type of engine.

The heat for the nuclear propulsion engine is generated by fission of the uranium-235 nucleus. Let us refer to this model. (Chart moves off and uncovers a back-lighted panel which is illuminated in the order described.) The uranium nucleus indicated here (switch on) is made up of 235 neutrons and protons. When an accidental neutron (switch on) enters this nucleus, it becomes unstable and explodes. This explosion breaks up (switch on) or fissions the nucleus into two pieces called fission fragments. The fission process blasts apart these fragments with enormous velocities. It is the slowing down of these high-velocity fragments by collisions with the surrounding atoms that generates most of the heat. In addition, gamma rays, which are very high-energy X-rays, are generated and two or more high-velocity neutrons are released. These newly born neutrons are now available to fission additional uranium nuclei and in this manner the reaction can be made self-propagating.

On the oscilloscope (above, center) is shown the results of an experiment in which a piece of uranium is being bombarded by neutrons. The occasional large pulses indicate actual fission processes. We can notice the random nature of these large pulses. The small pulses are caused by background radiation. The fission process can be re-enacted by using these large intermittent pulses to trigger the fission display (in back-lighted panel below).

The device in which uranium is located for the purpose of producing heat is called a nuclear reactor. The next chart (C-35910) illustrates one type of reactor. Uranium is arranged in a fuel element which is made of a structural material. The uranium is completely sealed within the fuel element to prevent the radioactive fission products from escaping. The heat that is produced by the fission is conducted to the surface of the elements and is picked up by a fluid flowing over these elements. The hot fluid is then piped to an engine which can convert the heat into power or thrust.

In order to regulate the rate of heat generation, movable control rods are provided. These control rods are made of material that is very absorptive of neutrons. Pushing the control rods into the reactor reduces the number of neutrons available for fission and therefore decreases the rate of heat generation. We must remember that neutrons born in fission move very fast, and at these speeds it is difficult for uranium nuclei to capture them. Therefore, materials called moderators, having light weight atoms such as hydrogen, beryllium, or carbon, must be built into the reactor to slow down the fast neutrons. These slow neutrons can then be more readily captured by uranium to produce new fissions.

The neutrons and gamma rays escaping from the reactor are fatal to personnel. It is, therefore, essential to shield personnel from these radiations. The shielding material is indicated here and I will talk about the problems of the shield in greater detail later.

Now then, just how is all the heat generated in the reactor to be converted into power? One of the simplest methods is to use the reactor to directly heat the air flowing through a turbojet engine. A conventional fuel-burning turbojet engine is shown on this chart (C-35907). Air enters and passes through this compressor and is then heated in this combustion chamber by gasoline fuel. The hot gases drive the turbine and expand through the exhaust nozzle to produce thrust. To convert this conventional engine to a nuclear powered engine, we replace the combustion chambers by a reactor. (Remove masonite overlay to expose reactor. This is chart C-35913.) The air is now heated in passing over the fuel elements of the reactor.

Now the heat-transfer rate to air is relatively low and forces us to go to large reactors to supply the power for supersonic aircraft. The shields required for these large reactors are very heavy.

One way to reduce shield weight is to get the required heat from smaller reactors. Smaller reactors can be obtained by cooling with a liquid which is a better heat-transfer medium than air. The next chart (C-35905) shows such a system. The liquid, circulated by a pump, picks up the reactor heat and carries it to a heat exchanger where the reactor heat is transferred from the liquid to the turbo-jet air. One of the difficult problems of this design is to find a liquid which has good heat transfer and good nuclear properties and which will not corrode the structural material of the reactor. More will be said about these problems by the following speakers. (remove chart.)

Let us return briefly to the shielding problem. The two types of radiation which are the most penetrating and for which shields are primarily designed, are the very fast neutrons and the gamma rays. To stop the fast neutrons we need moderating materials such as water or paraffin which will slow down these neutrons to speeds at which they are readily captured. To stop the gamma rays, high-density materials such as lead are desirable. To illustrate shielding principles, we have set up the following experiment. A radium-beryllium source of neutrons and gamma rays is located within this box (right of stage). The neutrons and gamma rays are generated by a nuclear reaction between radioactive radium and beryllium metal. The source is suitably shielded so that only a small beam impinges on these detectors (on brackets above source). The intensity of the fast neutron radiation is measured by this rate meter (on panel above source and detector) and the intensity of the gamma radiation is measured by this rate meter (above source). The slow neutron indicator will be used in a subsequent demonstration. We will have to wait a few seconds for the meters to reach equilibrium. These meters show random fluctuations at equilibrium characteristic of radioactive processes.

We will place this piece of paraffin (remove from hook, right center) between the source and the detectors, and observe the effect on the fast neutron rate meter. There is a drop in fast neutron count but note that the gamma count changes only slightly. If we add this piece of lead (remove from hook) between the source and the detectors and note the effect on the gamma rate meter, the gamma ray count is reduced appreciably with only a small effect on the neutron count. We can see that to provide adequate shielding, it is necessary to incorporate at least two kinds of materials in the shield; a moderating material to stop the fast neutrons, and a high-density material to stop the gamma rays. The weight of this shield is presently extremely high -- in fact, so high that it is very difficult to design a nuclear airplane which will fly at supersonic speeds. Research is required for development of lighter and more efficient shields.

Most of the NACA work has been concerned with the analysis of nuclear power plants and investigation of the heat-transfer and materials problems. The next speaker, Mr. Wachtl, will discuss the heat-transfer problems.

Part II - Reactor Heat Transfer

by William H. Wachtl, Warren H. Lowdermilk, and Armin F. Lietzke

Mr. Bogart described two power plants utilizing a nuclear reactor; the first was a system involving the direct cooling of the reactor by air, and the second was a more complicated system in which the reactor was cooled by an intermediate fluid. These are only two of the possible nuclear power plants that can be devised.

In order to accurately determine the performance of these reactors, and to properly design them, it is necessary to know the heat-transfer characteristics of various reactor coolants at the extremely high temperatures and heat flow rates that exist in the reactor. Improper design might result in overheating of the reactor fuel elements. The importance of an accurateknowledge of the heat-transfer characteristics of the coolants will be demonstrated with the following experiment:

Here we have a stainless steel tube in which heat is being generated at the extremely high rates that would be encountered in an aircraft reactor (upper left center of panel). The tube is being heated electrically by passing 1000 amperes through the walls of the tube, and cooled by flowing water through it. The rate of water flow is indicated by the height of the float in this flowmeter. The tube is now operating at a safe temperature. I will reduce the water flow by 5 percent, as will be indicated by the slight drop in the flowmeter reading, and as you will see, the tube will overheat, a hot spot will develop near the top of the tube, and the tube will burn out suddenly. The tube burns out because of a sudden decrease in the heat transfer characteristics of the water.

We run into peculiar phenomena like this when we simulate the cooling of a reactor with water at the very high heat flow and temperature conditions encountered within the reactor. It is apparent, therefore, that we must make a very careful study of the characteristics of reactor coolants.

When the NACA first looked into the problem, we found very little information on the heat transfer characteristics of air and water under the conditions that exist in a reactor, and even less information on other materials such as sodium, sodium hydroxide, lead-bismuth and lithium, which in their molten form have also been considered as reactor coolants. We therefore set up a research program to supply this information. In this work we established two lines of attack, one experimental and the other analytical. When the results of the two checked, we felt we had the situation well in hand.

We have shown on this chart (C-35906) a comparison between the experimental and the analytical results of the cooling ability for a number of coolants for flow through tubes. Excellent agreement was obtained between the experimental and analytical results for air, water, and sodium hydroxide. At the present time, for liquid metals there are differences between the results of various investigators for both experiment and analysis. Currently an intensive effort is being made to resolve this difficulty.

This chart also indicates the advantages of liquids over air as a coolant. These results are fundamental heat-transfer coefficients based on flow through tubes. This is not the complete story and more work must be done since, for practical reasons, we are sometimes forced to use arrangements other than tubes. One example of the heat transfer elements -- a stack of parallel plates -- is shown on the next chart (upper left of C-35908). This simple arrangement is not the best configuration for two reasons: First, flat plates do not have sufficient structural rigidity and are easily buckled by very large temperature gradients; and secondly, if we are limited by fabrication methods to a minimum spacing between the plates, more heat transfer area can be packed into the same volume with other arrangements. For example, merely by introducing vertical separators spaced the same distance apart as the plates (upper right of C-35908) we practically double the amount of heat transfer area within a given volume, and as a result, increase the heat flow rate. At the same time, we have made the structure considerably more rigid and resistant to deformation by the high temperature gradients. This is again purely an illustrative example and is not necessarily the best arrangement of the heat transfer elements. One of our important lines of work is to find the best arrangement of the heat transfer elements.

When we introduce these more complex passage shapes, as illustrated by this diagram (lower center of C-35908), we very often introduce sharp corners where the resistance to the coolant flow is high. In these corners, hot spots develop. One line of our work has been to investigate the temperature distribution around a number of passages of various shapes in order that we may be able to predict the temperature in these hotter corners.

In our heat transfer studies, we work very closely with the industrial organizations assigned the task of developing the nuclear aircraft engine and our research program includes projects which will provide the information needed by industry to help them design their reactors and solve their heat transfer problems.

Dr. Lad will now discuss the material problems of the nuclear reactor.

Part III - Reactor Material Problems

by Robert A. Lad, Burt M. Rosenbaum, and Robert W. Hall

Another critical problem is the development of satisfactory structural materials for use in the nuclear power plant. Satisfactory materials must meet several requirements -- they must have good nuclear characteristics, high strength at high temperatures, corrosion resistance, and they must be capable of withstanding the effects of prolonged radiation bombardment.

Any structural material within a reactor absorbs some of the neutrons with a consequent decrease in the number of neutrons available for initiating the fission process. This tendency of a material to absorb or capture neutrons is called the capture cross-section -- a high value for the cross-section corresponding to a high probability for neutron capture. Thus the requirement of good nuclear characteristics is equivalent to requiring small capture cross-section. This fact very drastically limits our choice of structural materials.

This chart (C-35909) lists the capture cross-sections for some representative metals. In order to demonstrate these facts, we again turn to the neutron source at this end of the platform (right of stage). We wish to measure the capture cross-section for slow neutrons because slow neutrons are more effective than fast neutrons in causing fission. Hence, we leave the paraffin (placed on by first speaker) in place to slow down some of the neutrons and actuate only the slow neutron meter (center on panel above source). I would like to remind you that these are rate meters and respond slowly.

The first metal on the chart is aluminum. When I place a plate of aluminum (remove from hook on panel right center) in the radiation beam, we notice very little reduction in the neutron count. This shows that aluminum has a low capture cross-section as shown on the chart and is satisfactory from the nuclear standpoint. Unfortunately, aluminum does not possess the necessary high-temperature strength inasmuch as it melts at 1200° F, a temperature much lower than is desired in aircraft reactors.

We next place a plate of iron in the beam (remove from hook on panel right center) and the resultant reduction in the reading indicates that iron has a higher cross-section. This higher cross-section means that careful design must be employed to minimize the amount of iron in a reactor. Also, because iron loses most of its strength at reactor temperatures, it is necessary to alloy iron with other metals. The stainless steels are such alloys.

Practically the first metal that comes to mind when we consider high-temperature alloys is cobalt, which is present as the major element in a large number of such alloys. When we test the cobalt plate, we see that this element has an extremely high cross section as indicated by the large reduction in the neutron count. Consequently, the extremely attractive cobalt alloys are useless in reactor design.

Since the coolant also occupies a position in the reactor such that it affects the neutron supply, its cross-section is also of importance. The chart also lists a number of coolant materials. Air, water, and sodium all have sufficiently low cross-sections to be usable. Lithium, in spite of excellent heat-transfer properties, cannot be tolerated as a coolant because of its high capture cross-section.

Materials of high capture cross-section, such as cadmium and boron, also have a place in reactors. They are useful in control rods whose control function depends on their ability to reduce the neutron population within the reactor. The effectiveness of cadmium is obvious when I interpose a cadmium sheet between the neutron source and counter.

I also mentioned corrosion resistance as a requirement. An important problem is that of finding materials that will resist corrosive attack by such coolant fluids as molten metals, salts, hydroxides or fluorides. Let us refer again to this coolant loop on the nuclear engine (C-35905). The fluid picks up heat in passing through the reactor and transfers heat to the heat exchanger. Two types of problem are encountered at the high temperatures involved:

1. The coolant penetrates and corrodes the surfaces over which it flows, weakening the structure of the enclosing tubes.

2. The coolant dissolves some of the material from the reactor elements and deposits this material on the cooler surfaces of the heat exchanger. This mass transfer action tends to plug the flow passages in the heat exchanger. Hence, satisfactory combinations of reactor structural materials and coolants are those for which neither of these two corrosive actions occurs at the flow rates and temperatures of interest.

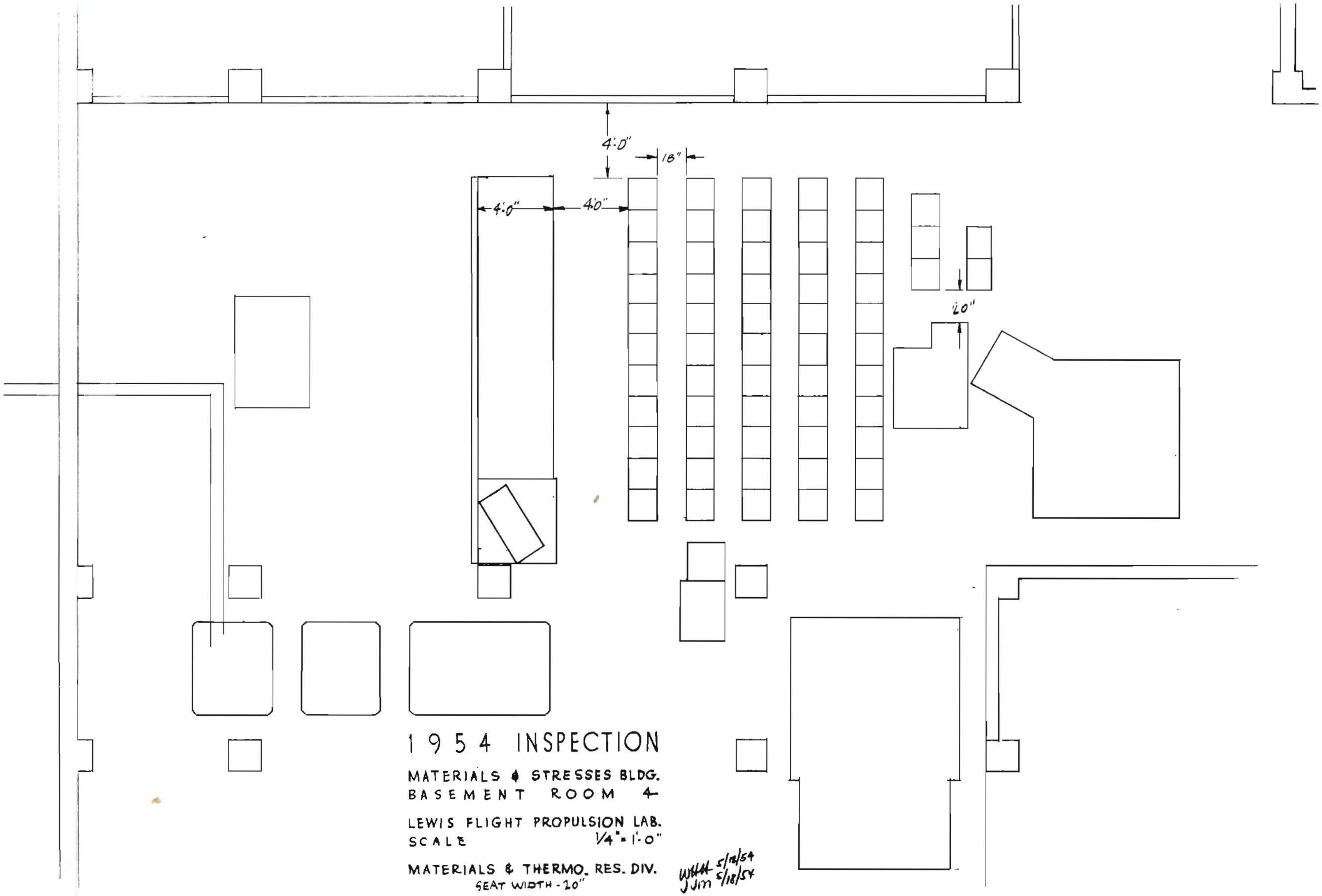
Now a satisfactory test should involve only the coolant and structural material in question, because the presence of a third material might alter the results of the test. This brings up the problem of how to circulate the fluid, since the incorporation of any standard pump would naturally introduce other materials into the flow circuit. To eliminate the necessity of building a pump out of every structural material under test, the NACA devised this apparatus in which circulation of the fluid is accomplished by an oscillatory motion. The material under test is made in the form of a tube bent into a loop. This is an example of such a tube (on panel, extreme left of stage). The coolant is then introduced into the tube, and when it fills approximately 40 percent of the volume, the tube is sealed off. The tube is then wrapped with heating coils to bring the system up to the temperature required. One section is cooled by an air blast to provide a temperature differential in the circuit. The assembly is mounted on a plate and the plate is oscillated by means of a motor in such a manner that the fluid is caused to circulate at a known speed. We have here a model of the apparatus used (extreme left of stage). Mounted on this plate is a glass tube partially filled with a colored liquid. The apparatus will be started and brought up to a speed which will clearly show the circulation of the fluid in the tube. In an actual experiment, the fluid circulates at a much higher rate than that shown here.

By means of tests using apparatus of this type, different combinations of coolants and structural materials were studied. The next chart (C-35870) shows a section cut out of a tube wall after a test. The magnification used here is 1000. This edge is the edge exposed to the flow of the fluid. As can be seen, the coolant has penetrated along the grain boundaries to a considerable depth, causing serious reduction in the strength of the material. This material proved completely unsatisfactory for use with the coolant under test. In tests with another material with this same coolant, we found an example of the second type of corrosive action in which the fluid deposits dissolved materials on the cooler tube surfaces. The next chart (C-35871) reveals what occurred in this instance. This section is from the hot portion of the loop, and this is from the cooler portion. You can see that metal was removed from the hot zone and redeposited in the cooler zone. Hence, this material likewise is unsatisfactory for our application because the continuous deposition of dissolved materials would eventually block the heat-exchanger tubes. In addition to the tests I have described, we also investigated various types of additives that can be dissolved in the coolant which will tend to inhibit both the corrosion and mass transfer effects.

The last requirement I will discuss is resistance to damage by the high flux of radiation present in the reactor. Metals suffer damage which results in changes in mechanical properties such as brittleness, hardness, strength, and dimensional stability. The choice must be made with these factors in mind.

This display (back-lighted panel, upper right center. Lighting is sequenced) illustrates the kind of damage done by radiation. The atoms in a material are normally arranged in a regular pattern as illustrated by the array of lights (first switch). When the U-235 nucleus is exploded in fission, the various fragments move at a very high velocity. We represent one of these fragments by this green light (second switch). When this fragment strikes an atom in the structural material of the reactor, it causes the atom to move out of its position at high speed (third switch). This atom and the original fragment go on to strike other atoms (fourth switch) and thus the number of atoms which are converted into missiles for knocking out other atoms increases at a fantastic rate. When the atoms finally come to rest (fifth switch), a large percentage of them end up in intermediate positions in the structure called interstitial positions, and an equivalent number of vacancies are formed in the regular array. (Repeat action several times without interruption.) A single fission fragment or a neutron released from the fission of a U-235 nucleus can displace as many as 100,000 atoms from their normal positions. This displacement of atoms in the structure causes changes in the strength, thermal conductivity, dimensional stability, and other properties. One of the current problems is to understand and to be able to predict the effect of radiation on the properties of substances situated within the reactor.

In this series of talks, we have endeavored to bring to you an understanding of some of the complexities involved in the design of an aircraft reactor. We have discussed three problems: shielding, heat transfer, and materials, and some of the methods that have been used to attack them.



1 9 5 4 INSPECTION

MATERIALS & STRESSES BLDG.
BASEMENT ROOM 4

LEWIS FLIGHT PROPULSION LAB.
SCALE 1/4" = 1'-0"

MATERIALS & THERMO. RES. DIV.
SEAT WIDTH - 20"

WHH 5/18/54
JJM 5/18/54

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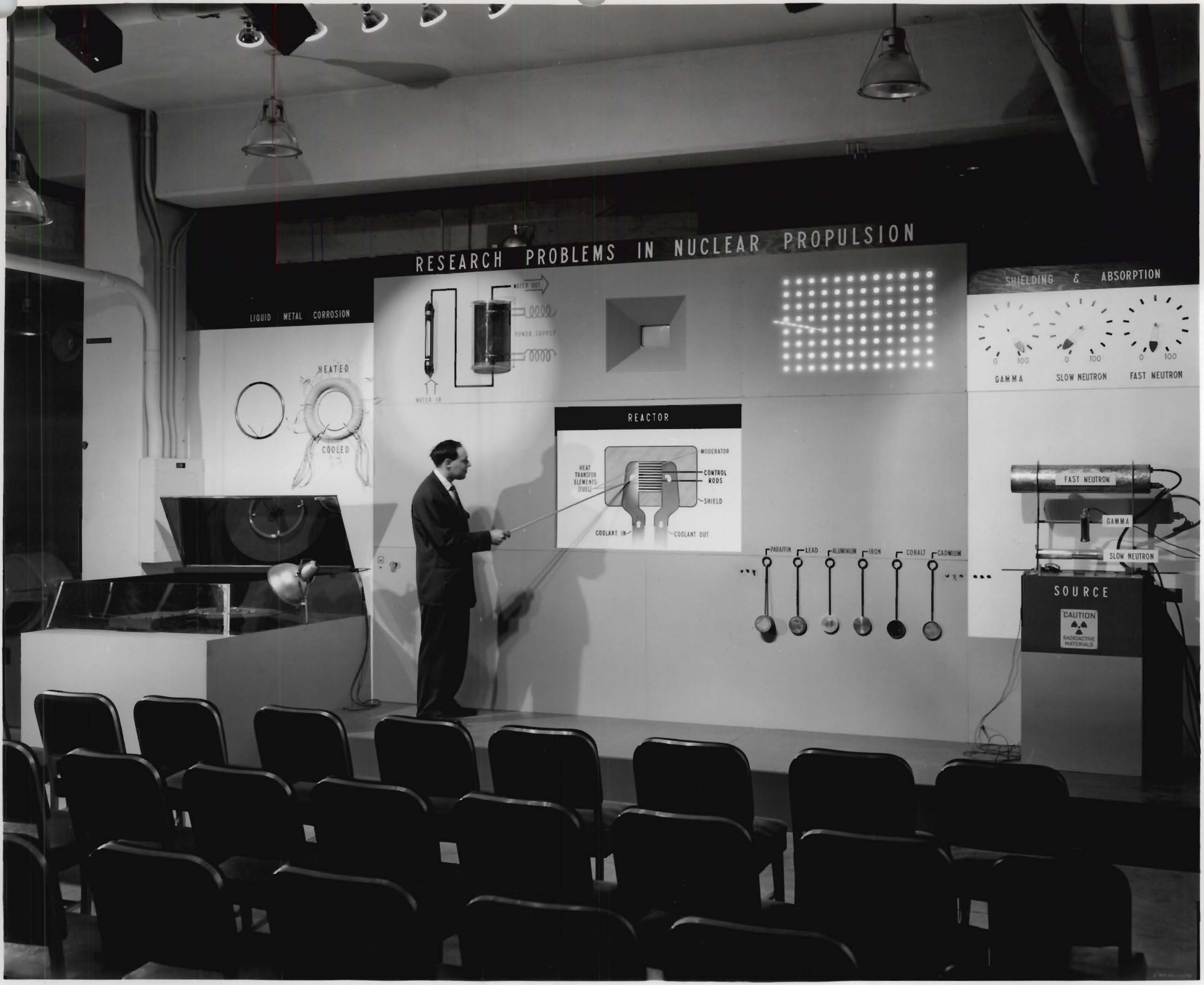
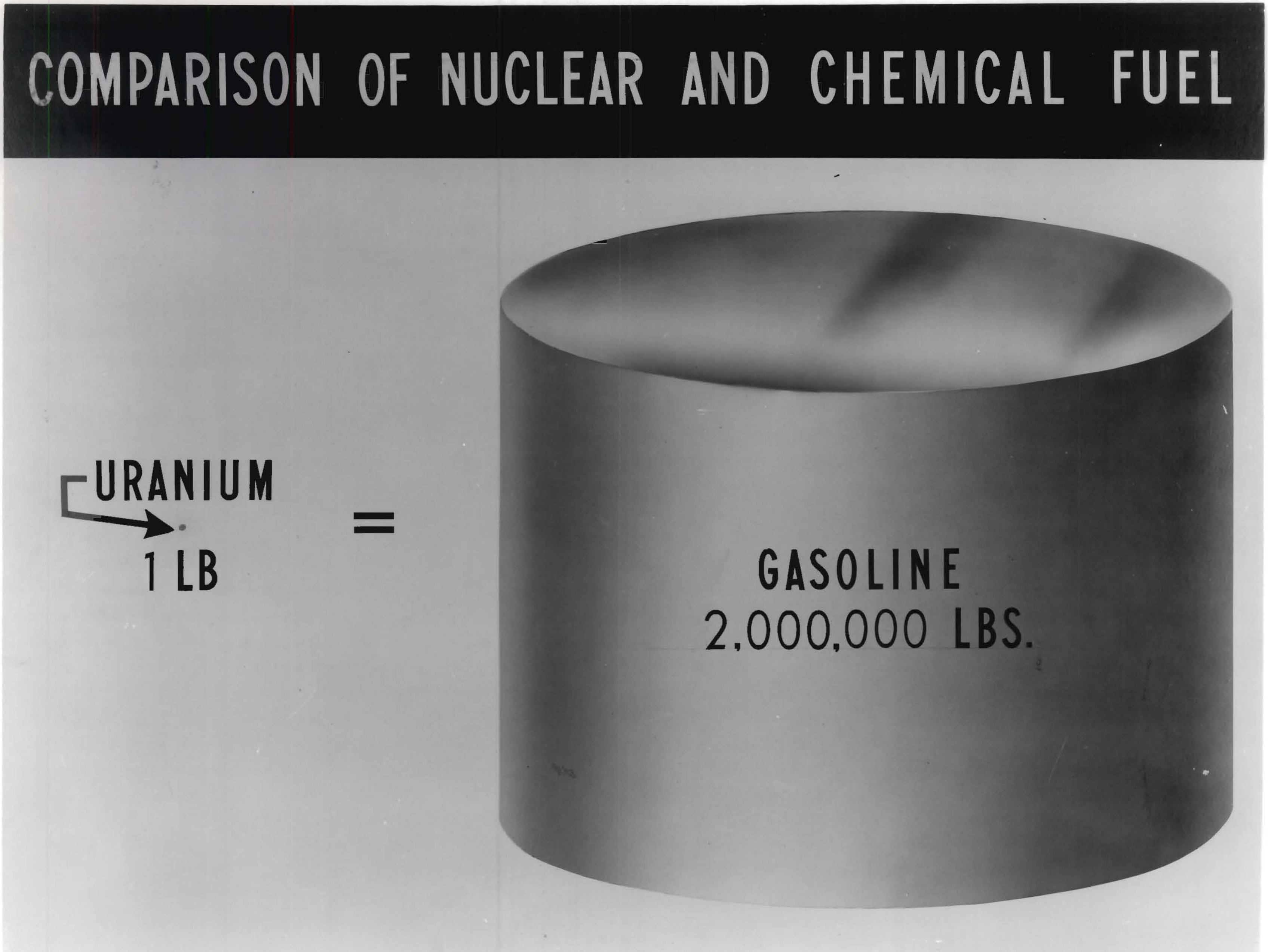


RESEARCH PROBLEMS IN NUCLEAR PROPULSION
LIQUID METAL CORROSION
HEATED
COOLED
WATER OUT
POWER SUPPLY
WATER IN
SHIELDING & ABSORPTION
0 100
GAMMA
0 100
SLOW NEUTRON
0 100
FAST NEUTRON
REACTOR
MODERATOR
HEAT TRANSFER ELEMENTS (FUEL)
CONTROL RODS
SHIELD
COOLANT IN
COOLANT OUT
PARAFFIN
LEAD
ALUMINUM
IRON
COBALT
CADMIUM
FAST NEUTRON
GAMMA
SLOW NEUTRON
SOURCE
CAUTION
RADIOACTIVE MATERIALS


COMPARISON OF NUCLEAR AND CHEMICAL FUEL
URANIUM
1 LB
=
GASOLINE
2,000,000 LBS.

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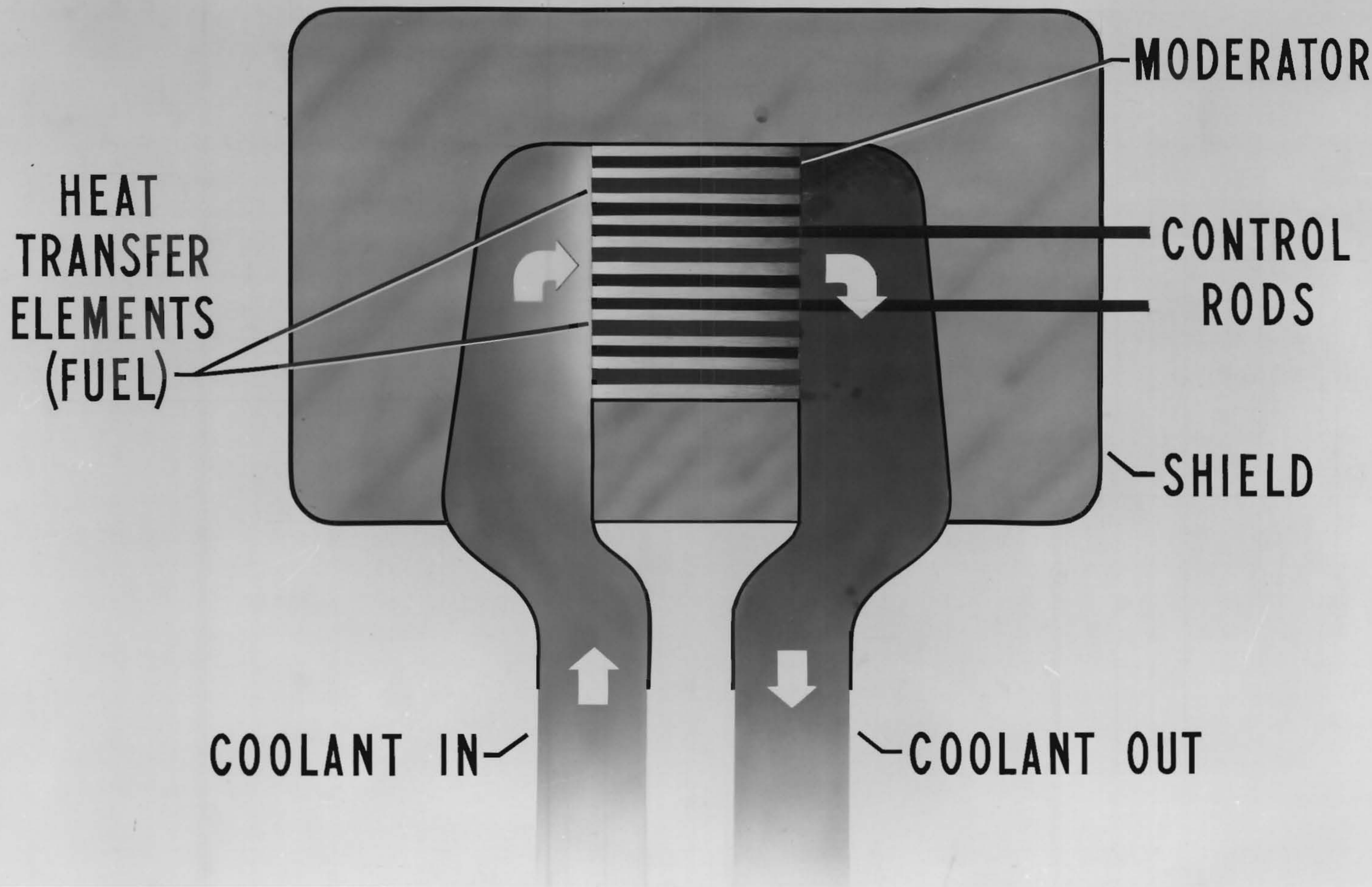
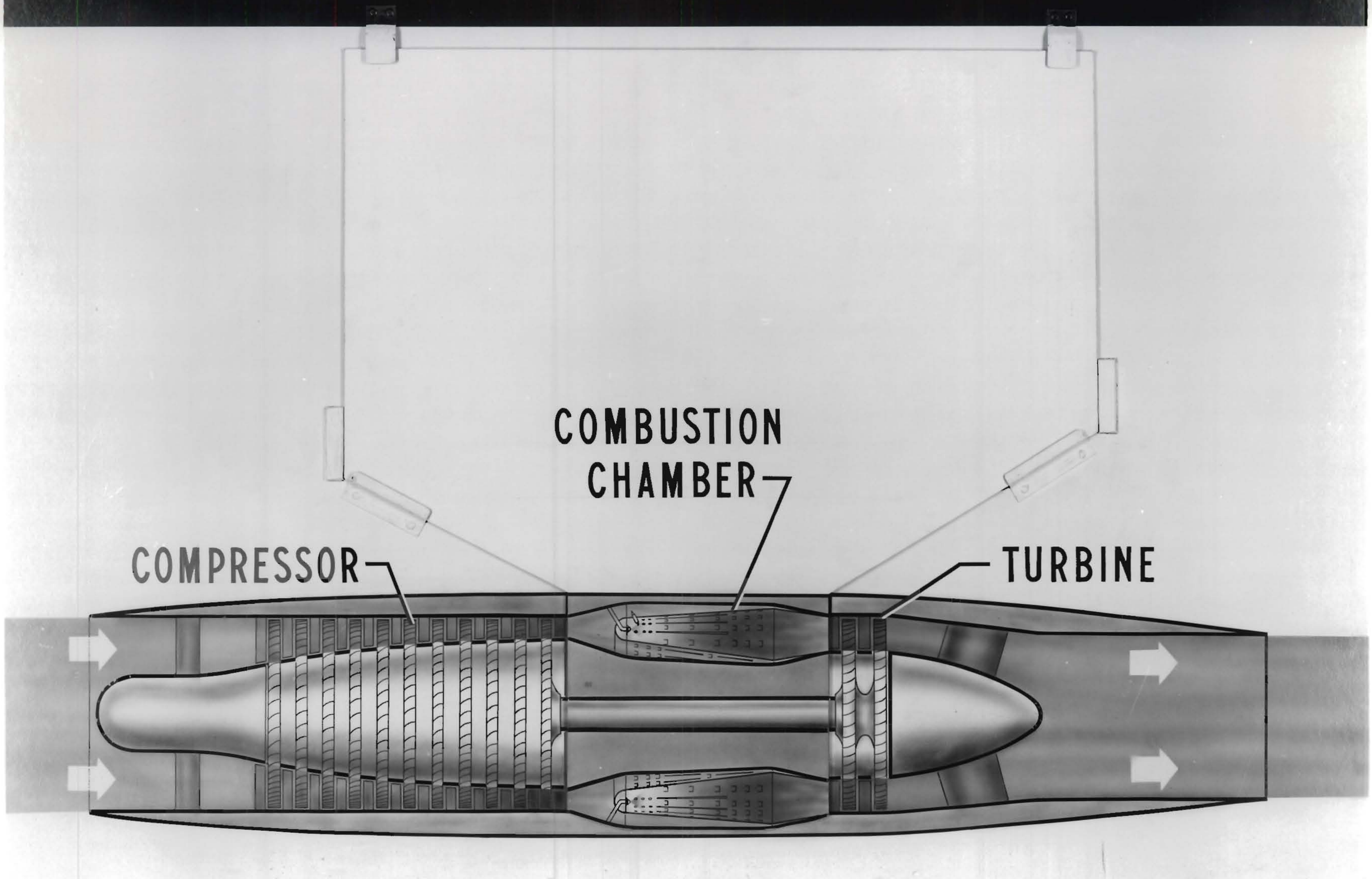
35910

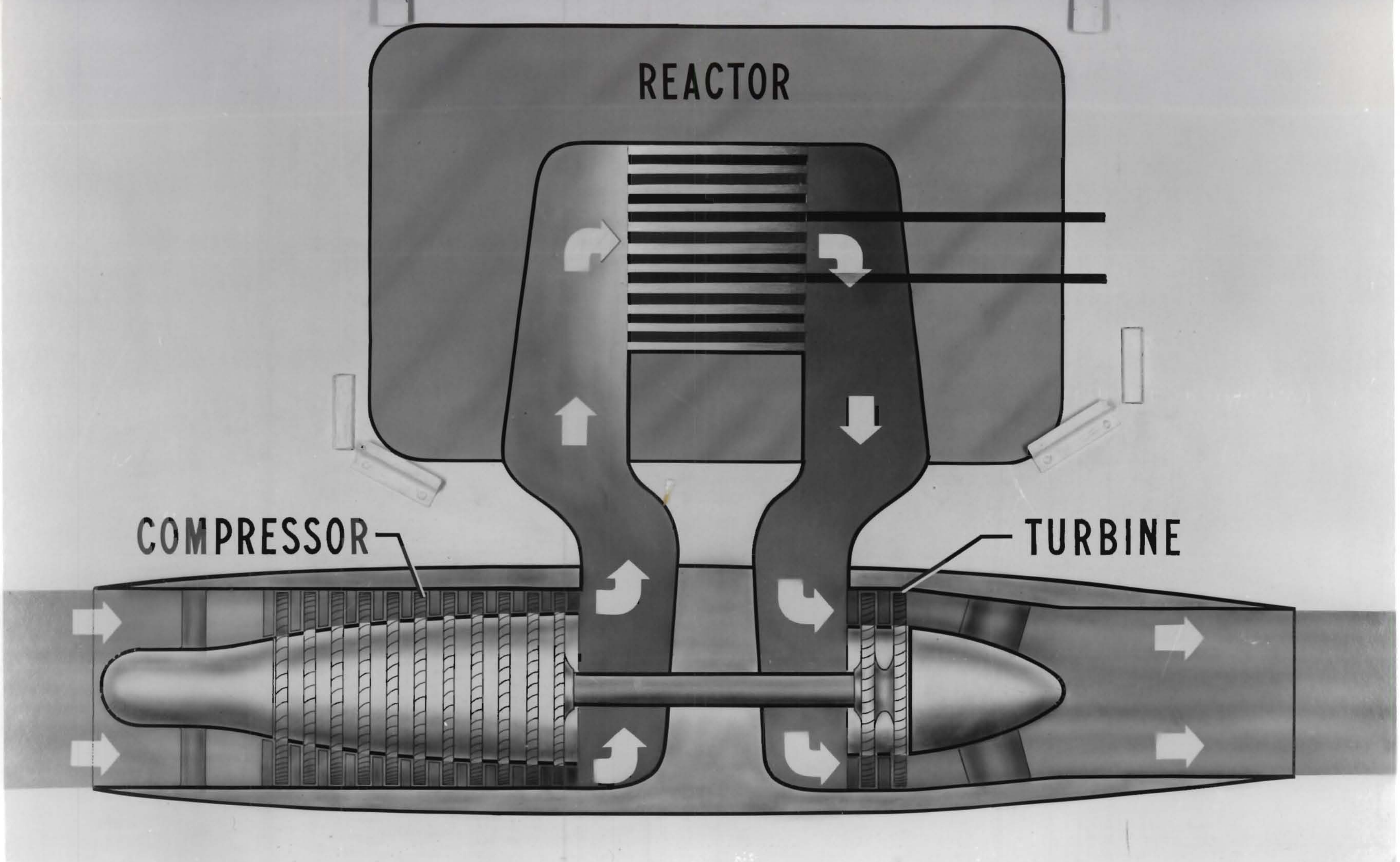
REACTOR



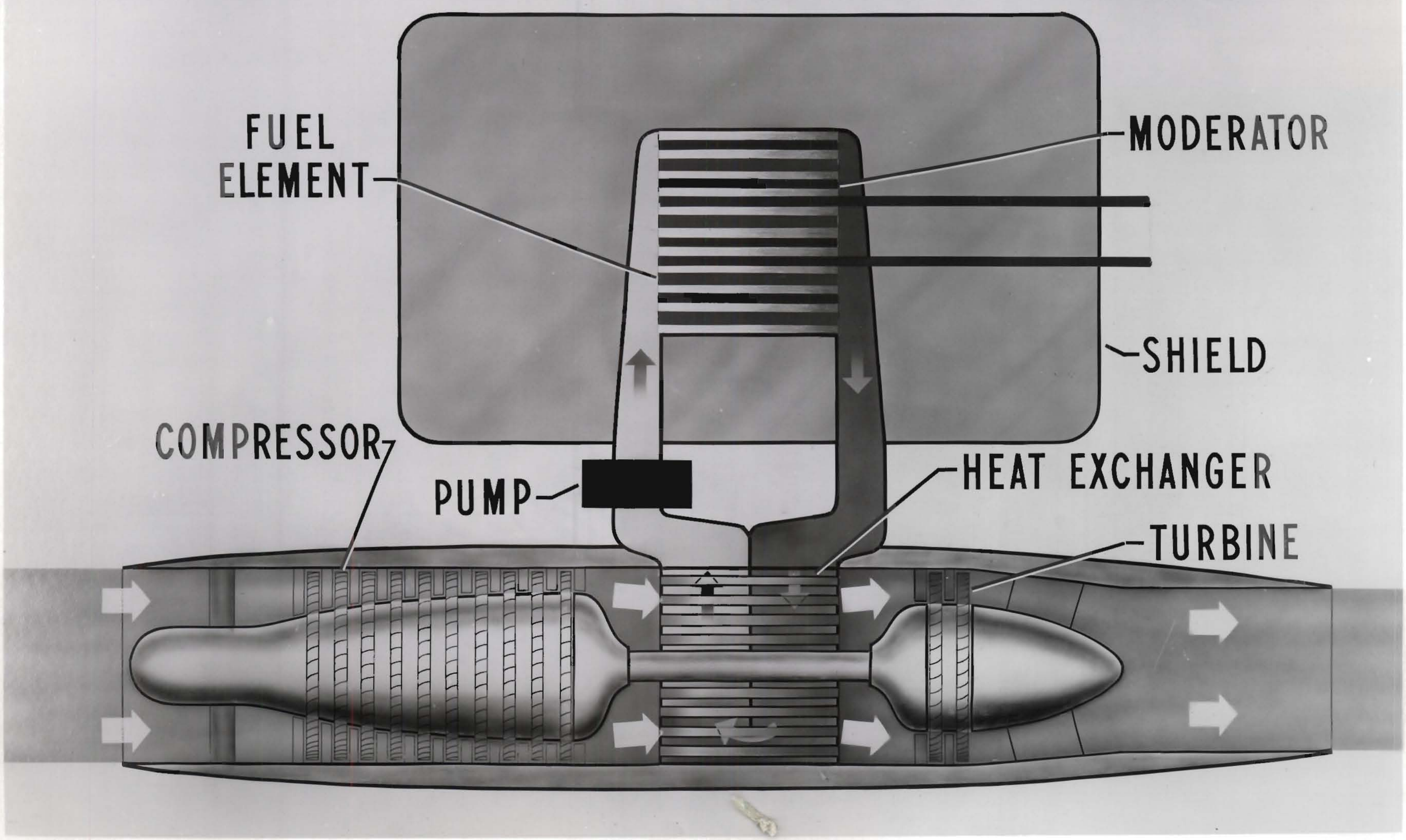
DIRECT AIR CYCLE



DIRECT AIR CYCLE



LIQUID COOLED REACTOR CYCLE



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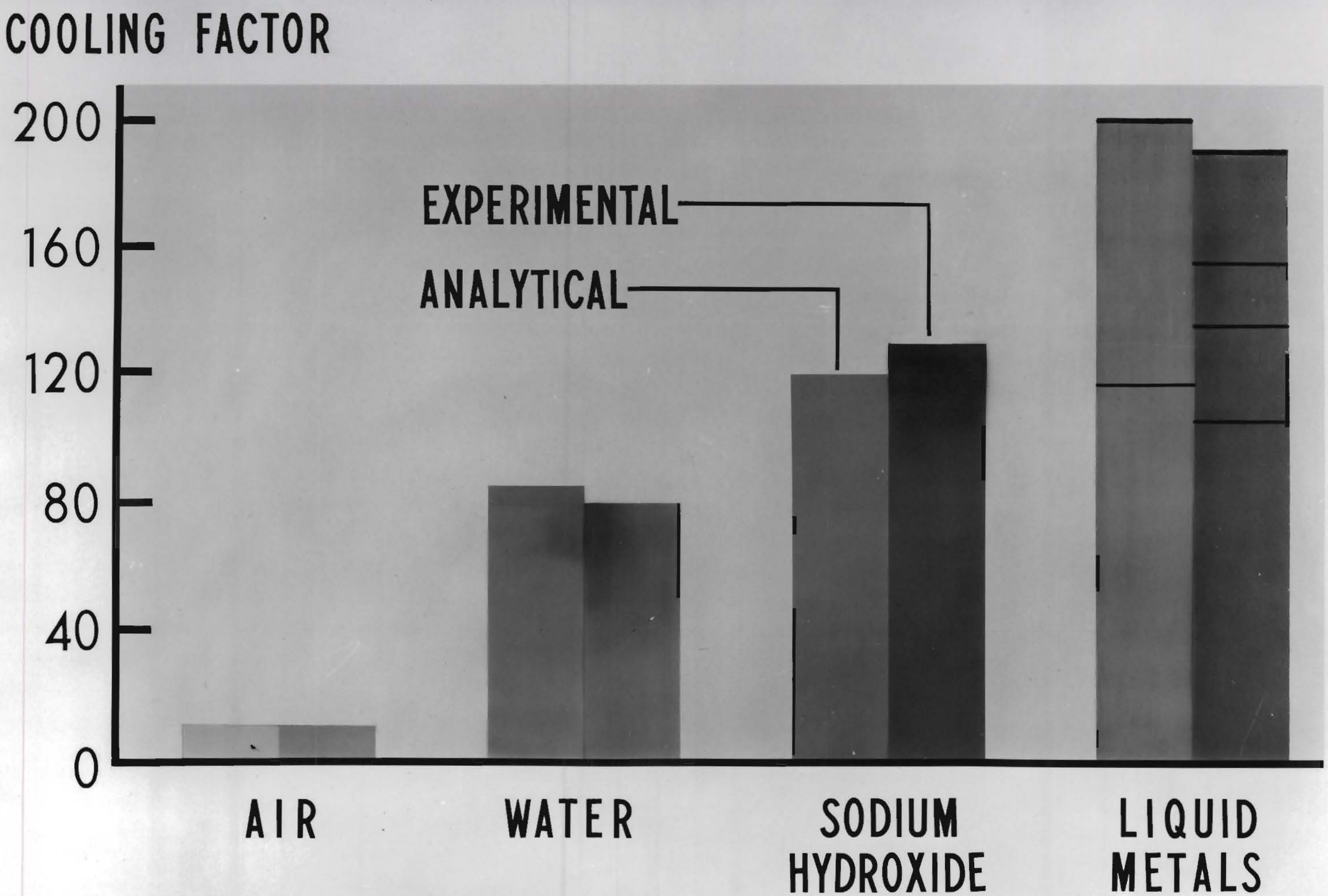
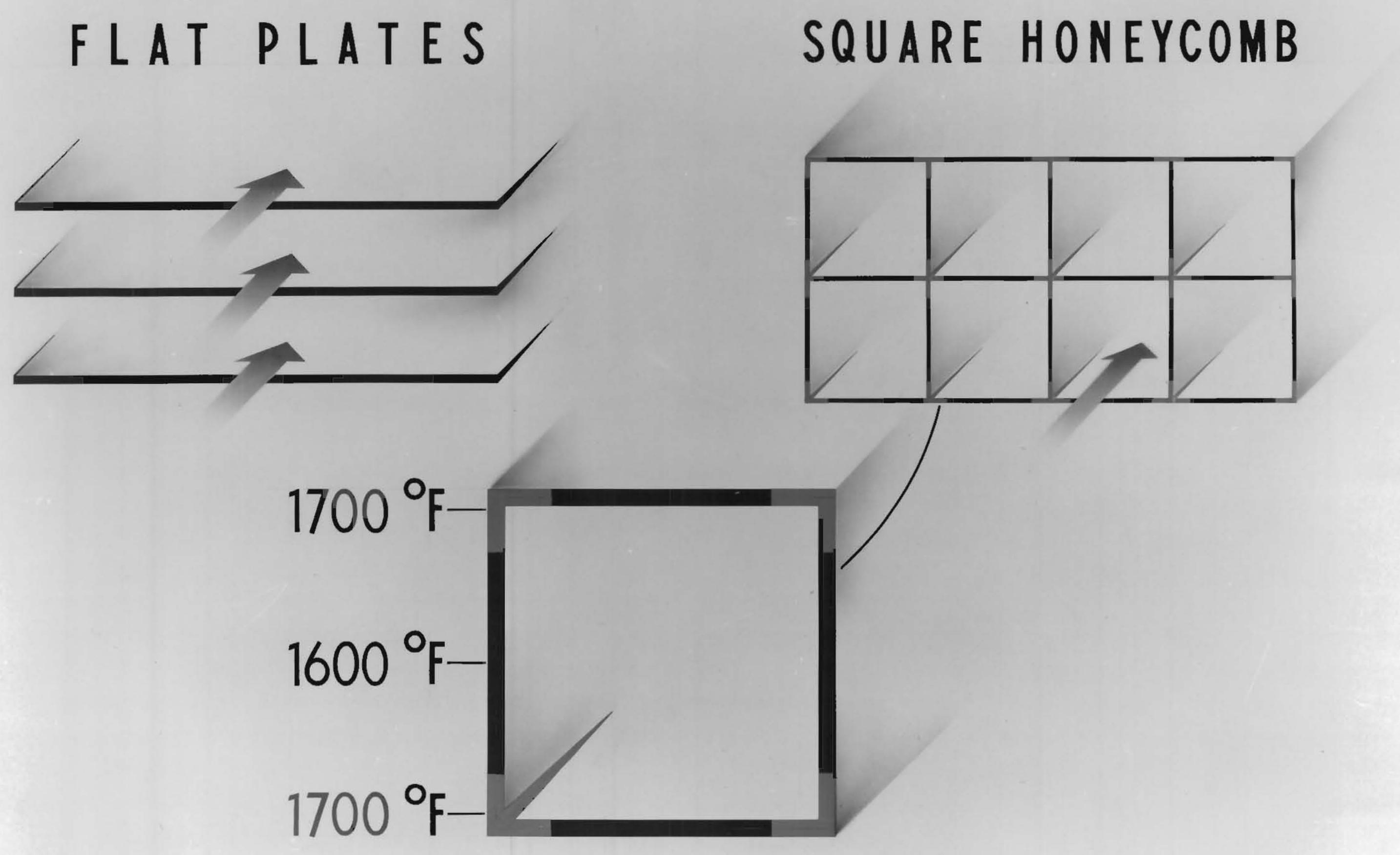
C-35906

COMPARISON OF POSSIBLE COOLANTS



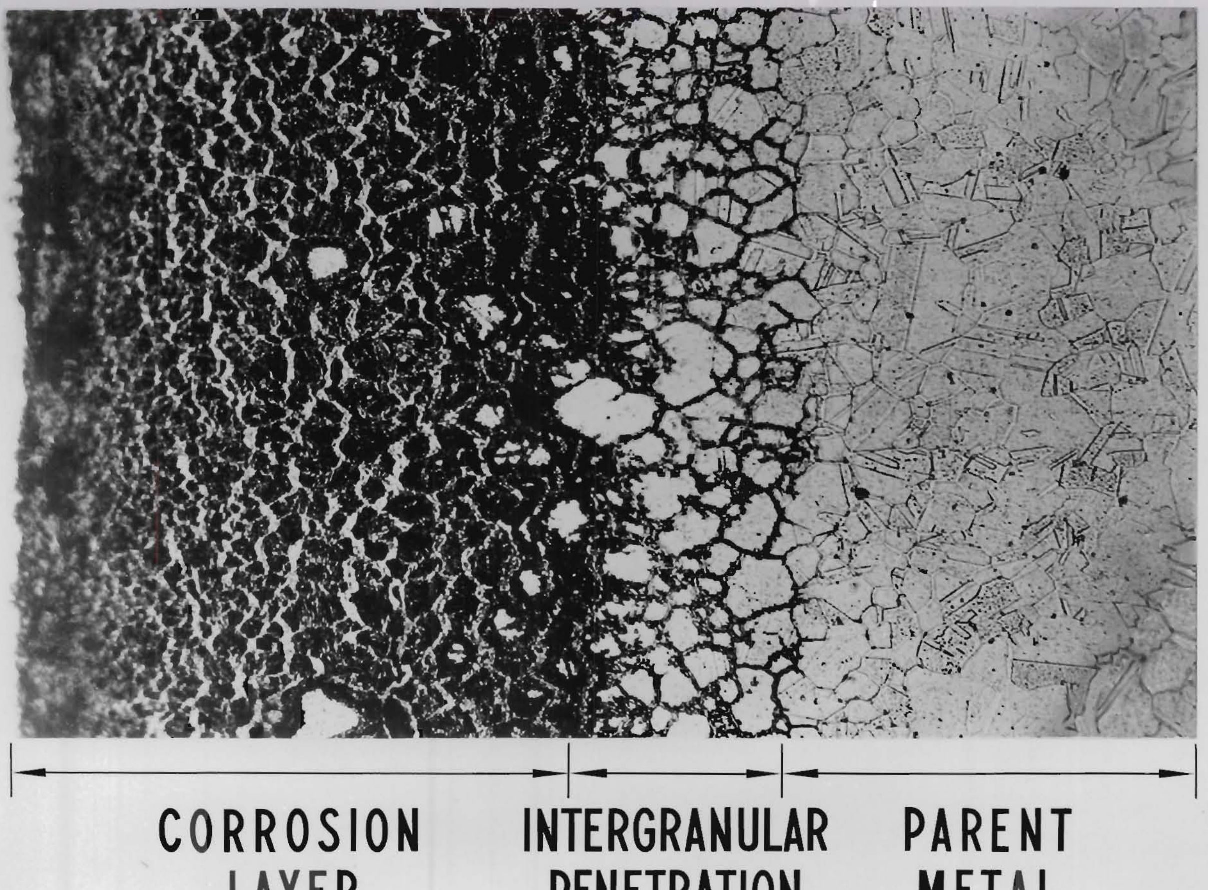
HEAT EXCHANGER CONFIGURATIONS



CAPTURE CROSS SECTIONS OF REPRESENTATIVE MATERIALS

STRUCTURAL MATERIALS	ALUMINUM	0.22
	IRON	2.4
	COBALT	36.0
CONTROL ROD MATERIALS	BORON	750.0
	CADMIUM	2400.0
COOLANTS	SODIUM	0.49
	WATER	0.64
	LITHIUM	65.0

CORROSION OF STRUCTURAL MATERIALS BY A COOLANT



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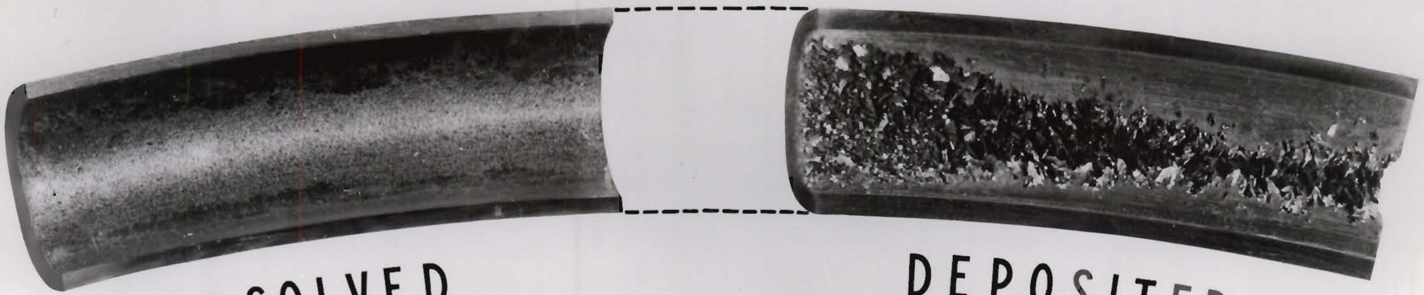
MASS TRANSFER OF STRUCTURAL MATERIALS BY A COOLANT



FLUID

HOT → COOL

FLOW